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A Technique for Predicting Fly Ash Resistivity

Southern Research Inst, Birmingham, AL

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A Technique for Predicting Fly Ash Resistivity

Interagency Energy/Environment R&D Program Report

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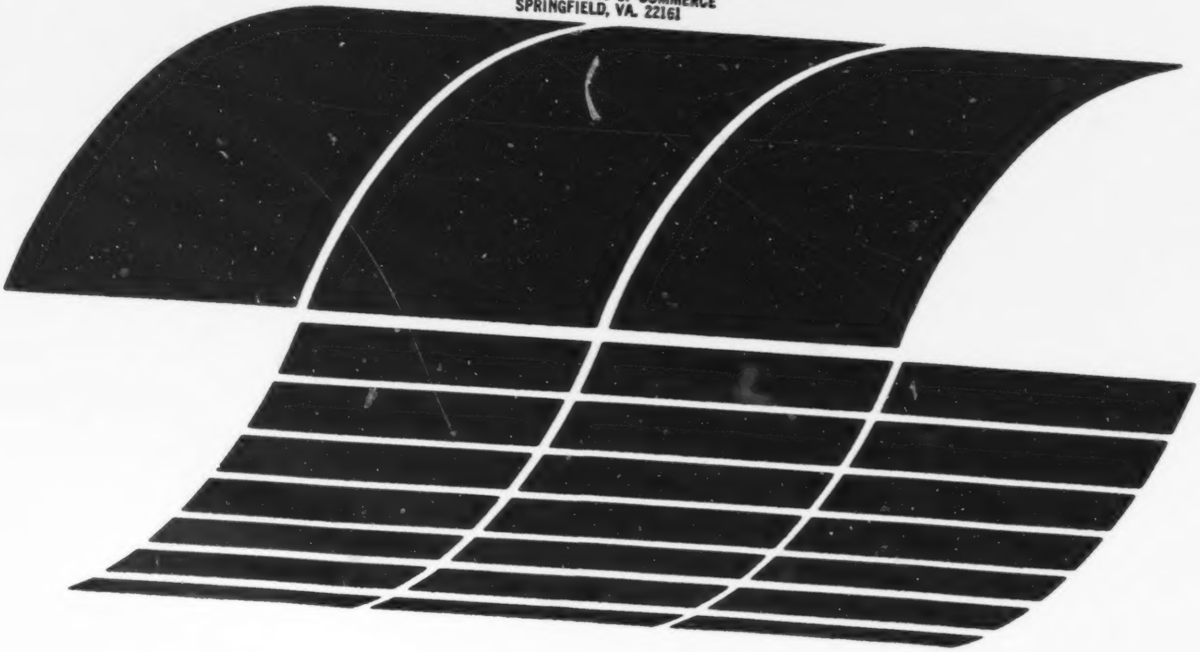

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16. ABSTRACT

The report gives results of research to develop a technique for predicting: the electrical resistivity of fly ash from an as-received, ultimate coal analysis; and the chemical composition of the concomitant coal ash produced by simple laboratory ignition. Important chemical factors are the alkali metals, alkaline earths, and iron (with respect to the fly ash), and the water and sulfur trioxide concentrations in the flue gas. Many fly ash samples were evaluated to minimize variations due to physical effects. The effects of fly ash chemical composition, ash layer field strength, and the water and sulfur trioxide concentrations in the test environment were evaluated with respect to electrical resistivity and the evaluated parameters for the entire temperature spectrum of interest. Equipment and techniques were developed to obtain the required data. Predicted sensitivity as a function of temperature was favorably proof-tested using data acquired from previous field evaluations of precipitators at six power generating stations. The proof test involved a comparison of predicted resistivity, laboratory measured resistivity, resistivity measured in situ, precipitator efficiency, and current density of the precipitator outlet fields.

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Fly Ash	Alkaline Earth Compounds	Stationary Sources	21B	
Electrical Resistivity			20C	
Chemical Composition			07D	
Forecasting	Iron		14B	
Coal	Electrostatic Precipitators		21D	
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A Technique for Predicting Fly Ash Resistivity

by

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ABSTRACT

The objective of the research reported herein was to develop a technique for predicting the electrical resistivity of fly ash from an as-received, ultimate coal analysis and the chemical composition of the concomitant coal ash produced by simple laboratory ignition. This research was motivated by the obligatory need to know this particulate property. The information is required or extremely useful for designing a dry-collecting electrostatic precipitator, for evaluating the quality of coal in an unopened seam or field, and for blending coals to produce a desired effect.

The electrical resistivity of fly ash is dependent on several physical and chemical characteristics of the particulate and the flue gas. Physically, the particle size distribution, specific surface and ash layer porosity are important. Chemically important are the alkali metals, alkaline earths and iron with respect to the fly ash and the water and sulfur trioxide concentrations in the flue gas. Since the technique for predicting resistivity does not anticipate physical parameters, a large number of fly ash samples were evaluated in this research to minimize variations due to physical effects. The effects of fly ash chemical composition, ash layer field strength, and the water and sulfur trioxide concentrations in the test environment were evaluated with respect to electrical resistivity in the laboratory. Correlations were established between resistivity and the evaluated parameters for the entire temperature spectrum of interest. The research became especially difficult when it was discovered that conventional resistivity test apparatus and procedures were not applicable to investigating the effect of sulfur trioxide on resistivity. Suitable equipment and techniques were developed to obtain the required data.

It was previously observed and reconfirmed in this work that the chemical composition of fly ash and coal ash are similar if the fly ash has a relatively low concentration of combustibles and the coal ash has been ignited in air at a sufficiently high temperature, $\sim$1050°C. The coal ash chemical composition and the flue gas analysis calculated from the stoichiometric combustion of the coal were used to predict resistivity using the aforementioned correlations.

Predicted resistivity as a function of temperature was favorably proof tested using data acquired from previous field evaluations of precipitators at six power generating stations. The proof test involved a comparison of predicted resistivity, laboratory measured resistivity, resistivity measured in situ, precipitator efficiency, and current density of the precipitator outlet fields.

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SECTION 1

INTRODUCTION

In the design of an electrostatic precipitator for the dry collection of fly ash, the electrical resistivity of the ash is one of several important factors to be considered. Since resistivity inversely influences the allowable electrical operating parameters, high resistivity necessitates the design of large precipitators for a given collection efficiency. The direct relationship between the size and performance of the precipitator and the cost makes the knowledge about resistivity mandatory.

When a precipitator is being sized to collect ash produced from a well known coal of uniform character, performance data and/or in situ resistivity data are available, and minimum design difficulty is encountered. However, ash produced from coals of highly variable character or from coals that have not been previously commercially burned present a problem. If a trial burn of a coal of unknown quality at a commercial installation to obtain design data is not possible, one must acquire this information in some other manner.

Precipitator manufacturers have proprietary techniques for estimating fly ash resistivity and precipitator design functions. Often these techniques, developed from extensive experience, are based on a correlation in which certain coal, coal ash or fly ash characteristics are related to previous success or failure in the precipitator design. Usually these procedures are not publically available and often are not generally applicable. An alternate approach[1] is to burn small quantities of pulverized coal in small furnaces and measure the properties of the resultant fly ash. Although time consuming and expensive, this technique should give excellent results if the fly ash and the flue gas duplicate those commercially produced. Using this method, one can examine the physical, chemical, and electrical characteristics of the fly ash.

Several years ago relationships were developed[2,3,4] between fly ash resistivity and certain parameters that are based on the chemical composition of fly ash. With these relationships one can predict the resistivity of fly ash for specific conditions or types of ash knowing the chemical composition of the fly ash or coal ash. Resistivity predictions obtained in this manner have been used with a substantial degree of success.

These ash composition-resistivity correlations have some inherent weaknesses. The data used to establish the correlations are obtained from laboratory resistivity tests conducted under a limited number of conditions. Generally these conditions involve low ash layer field strength, invariant environmental water concentration, and the absence of sulfur trioxide from the test environment. Furthermore, disagreement was often noted between laboratory resistivity determinations and *in situ* values; however, one cannot assume that all *in situ* data are infallible. In spite of the shortcomings, these predictive techniques are reasonably effective when applied to ashes of low-sulfur coals, because they take into consideration the temperature and the concentration of sodium in the ash. These two factors exercise the principal control over ash resistivity values when the sulfuric acid vapor in the flue gas is insignificant.

There has been an intense motivation to be able to predict fly ash resistivity quickly, cheaply, and accurately in the absolute sense from the most basic of input data. This ability would allow one to:

- supply input data for sizing precipitators with respect to one or many design coals,
- topographically define the resistivity for entire unopened coal fields or seams from core bore samples,
- troubleshoot poorly performing precipitators without *in situ* resistivity measurements,
- develop an in-line monitor for stockpiled coal feed,
- blend coals to obtain superior precipitation characteristics,
- evaluate the merits of hot-side or cold-side operations,
- evaluate and/or select dosages of conditioning agents.

Encouraged by laboratory resistivity measurements that produce data in better agreement with *in situ* values and by the observation that in most cases fly ash composition and concomitant coal ash composition are similar, additional research was proposed to develop an improved technique for predicting the resistivity of fly ash. The objective of the research was to produce a predictive technique that requires as input information the as-received, ultimate coal analysis and the chemical composition of the respective coal ash. The output information is resistivity as a function of temperature for a given coal ash analysis in an environment stoichiometrically calculated from the coal analysis. This report describes the results of this research.

SECTION 2

CONCLUSIONS

As a result of this research, a technique for predicting the electrical resistivity of fly ash from an as-received, ultimate coal analysis and a chemical composition of the coal ash was developed. Resistivity predicted as a function of temperature was favorably proof tested by comparing predicted resistivity values with those acquired by *in situ* and laboratory measurements.

A prerequisite step to the accomplishment of the task objective was the design of equipment and a test procedure to quantitatively evaluate the effect of environmental sulfur trioxide on the electrical resistivity of fly ash. This was successfully performed, and additional information related to the conduction mechanism involving sorbed sulfuric acid vapor was obtained. It was concluded that the effect of sorbed sulfuric acid vapor was observable only while the agent was being continuously injected and that the conduction process functioned independently of other surface conduction mechanisms.

SECTION 3

RECOMMENDATIONS

The effort to develop the method for quantitatively evaluating the effect of environmental sulfuric acid vapor on resistivity required a large amount of contract time. As a consequence, the amount of data taken after the perfection of this experimental procedure was held to the minimum that would still permit the development of the resistivity predictive technique. Therefore, it is suggested that additional experimentation should be conducted to perfect that portion of the predictive technique related to environmental sulfur trioxide. Specifically, more data are needed with respect to: (1) the variation of sulfur trioxide concentration, (2) the combined effect of variations in water and sulfur trioxide concentrations, and (3) the relationship between the effectiveness of sulfur trioxide and the fly ash composition.

Additional effort should be made to evaluate the predictive technique with respect to: (1) cleaned coal, (2) the effect of conditioning agents, and (3) the effect of coal containing large amounts of ash and moisture thereby yielding a stoichiometrically high concentration of sulfur trioxide for a relatively low concentration of sulfur in the coal. This effort would require a combined field testing - laboratory experimentation task.

In this report a simple coal ashing technique was used that was selected based on a few trial and error experiments. It is recommended that a technique be developed to objectively select the temperature at which a given coal should be ignited to produce the coal ash required for the prediction of fly ash resistivity.

The technique for predicting fly ash resistivity described in this report utilizes a sulfur trioxide concentration calculated as a percentage (0.4%) of the sulfur dioxide concentration obtained from the stoichiometric combustion of the coal. Furthermore, it is assumed that the fly ash is in equilibrium with the concentration of the sulfur trioxide that is measured at the precipitator inlet and that this is also true of the fly ash layer under laboratory test when exposed to a given sulfur trioxide concentration for a long period of time, typically 18 hours. A task combining field evaluation and laboratory experimentation is required to justify the above approach. Typical of some of the data required would be _in situ_ resistivity and flue gas analyses taken at about 350°C and 150°C. This information would be coupled with coal and fly ash analyses and laboratory resistivity data obtained under conditions simulating the _in situ_ conditions.

SECTION 4

INVESTIGATIVE SCOPE AND APPROACH

A large number of commercially produced fly ashes were chemically and physically characterized for this work. It was hoped that all ranks of coal would be represented. Resistivity as a function of temperature for a given set of electrical and environmental conditions was determined using all the available fly ash specimens. From these data one can relate fly ash resistivity as a function of temperature to fly ash chemical analysis for one set of experimental conditions.

From the original group, sixteen ashes were selected to investigate the effect of the variation in environmental water concentration and ash layer field strength on resistivity. Eight of these ashes were further utilized in experiments to determine the effect of sulfur trioxide on resistivity. By combining the expressions defining the effects of these three factors on resistivity with the basic expression for resistivity as a function of ash composition, resistivity can be predicted as a function of temperature knowing the ash composition, water and sulfur trioxide concentrations, and the ash layer field strength.

Six coal and fly ash specimens were obtained during field test programs in which in situ resistivity and precipitator electrical characteristics were monitored. Experiments were conducted to establish an ash ignition temperature that produced coal ashes that were chemically similar to their respective fly ashes. From these coal ash analyses and the water and sulfur trioxide concentrations estimated from stoichiometric combustion calculations, resistivity was predicted. This predicted resistivity value was compared to the resistivity values determined in the laboratory, the in situ resistivity data, and the precipitator electrical operating conditions.

SECTION 5

EXPERIMENTAL PROCEDURES

FLY ASH AND COAL CHARACTERIZATION

The fly ashes were received from commercial steam generating power plants. An organization supplying fly ash samples also submitted a data sheet listing the available information regarding coal identification and analysis, flue gas analysis, precipitator temperature, source of ash sample, etc. After the ashes were put through an 80 mesh screen to remove debris, they were quartered into 25-gram specimens to be used for resistivity and characterization studies.

The chemical composition, helium pycnometer density and particle size distribution were determined for each fly ash. Helium pycnometer density was determined using a Micromeritics Instrument Corporation, Model 1302 helium-air pycnometer using the manufacturer's suggested procedures. A number 6000 Bahco Micro Particle Classifier was used to determine the particle size distribution using the technique outlined by the manufacturer. Chemical analyses were conducted for the elements commonly reported for fly ash. In addition, soluble sulfate and loss on ignition were determined. The chemical analyses were made using ash specimens that had been ignited for loss on ignition determination. A general description[5] of the analysis procedure for fly ash and the gaseous environments used is available.

Representative coal specimens were sent to a subcontractor to have total sulfur, proximate analysis, ultimate analysis, and forms of sulfur determined. Respectively, the ASTM designated procedures used for these determinations were: D3117, D3172, D3176, and D2492. In addition, the subcontractor ashed one-pound samples of coal using the ASTM procedure D3174 (700-750°C). These coal ash samples provided the starting material for the ignition experiments which will be subsequently discussed.

EXPERIMENTAL EQUIPMENT AND PROCEDURES FOR RESISTIVITY DETERMINATION

This research required the determination of resistivity using simulated flue gas environments. Major experimental problems were encountered when using sulfur oxides. These difficulties included the technique of environmental chemical analysis, the inadvertent generation of sulfur trioxide and the need to develop a resistivity test procedure involving sulfur trioxide. A significant effort was required to overcome these problems, ultimately a new test procedure and resistivity test cell were developed to evaluate the effect of sulfur trioxide on fly ash resistivity. Since the equipment and test procedures used represent a departure from the commonly employed techniques, a separate report[6] regarding this facet of the research was written. Consequently only a brief description of the apparatus and procedures used to measure resistivity will be given here.

The initial apparatus consisted of four ASME, PTC-28[7] test cells housed in a stainless steel environmental chamber which was installed in a high temperature laboratory oven. A negative, direct-current high voltage was supplied in common to the cup style electrodes. Each current measuring circuit and guard ring circuit terminated at a female phone jack. A male phone jack was used to complete the circuit under test. Except when the effect of ash layer field strength was examined, the applied voltage was 1330 volts (2 kV/cm). The standard baseline environmen in addition to nitrogen contained by volume 5% oxygen, 13% carbon dioxide, 9% water, and 500 ppm sulfur dioxide. The simulated flue gas environment was maintained under slight positive pressure in the chamber.

The resistivity as a function of temperature was determined using the above conditions for each fly ash used in the project. The ash under test was allowed to thermally equilibrate overnight at 460°C in a dry nitrogen environment. After determining the resistivity under this condition, the environment was changed to the above described baseline mixture. Approximately thirty minutes later the oven was turned off and allowed to cool naturally. Resistivity and temperature were recorded periodically as the test cells cooled to 85°C. After removing the test cell from the chamber, the ash layer thickness was determined, and resistivity was calculated in the usual manner.

Using the apparatus and procedure briefly described, tests were repeated on sixteen of the ashes to examine the effect of water concentration and field strength on resistivity. In addition to the baseline value of 9%, water concentrations of 5% and 14% were used. When the effect of field strength was being determined, the test procedure was slightly altered in that the oven cooling process was arrested at 162°C. At this temperature the effect of field strength was measured by increasing the applied voltage in increments of 1330 volts until dielectric breakdown occurred or the capacity of the voltage supply (6000 volts) was reached.

The apparatus and procedure used to determine the effect of temperature, ash composition, water concentration and field strength on resistivity was unsatisfactory for experiments involving sulfur trioxide. A second test apparatus was constructed principally of glass that could accommodate one test cell. In the case of the modified resistivity test cell, two circular, concentric electrodes 1-mm thick were pressed into the surface of an ash layer to a depth of 1 mm. Voltage was applied across a 6-mm gap between the electrodes, and the current was measured. This thin layer of ash contiguous with the test environment was capable of equilibrating with the sulfuric acid vapor in a reasonable amount of time.

The standard test environment was changed from a simulated flue gas to air containing 9% water. The effect of sulfur trioxide on resistivity was determined for concentrations of about 5 and 10 ppm using the air-water environment.

The test procedure was altered significantly also. Isothermal tests were usually conducted at 138, 147, and 166°C. The ash was equilibrated in dry air at the temperature of interest for three hours. After determining dry resistivity, the nine percent moisture was introduced. Current was measured every five minutes (voltage applied one minute), and when the value failed to increase, the sulfur trioxide was introduced. An overnight equilibration was required for the resistivity to asymptotically approach a minimum value. The environmental moisture concentration and sulfur trioxide concentration were determined after the first hour of the test and during the final hour. Resistivity was calculated using the expression derived for a radial flow (concentric electrodes) test cell, and the soluble sulfate concentration for the ash before and after test was recorded.

The equipment and procedures described in reference 6 for making laboratory resistivity determinations in an environment containing sulfuric acid vapor represent a noteworthy technical advancement. At present it is the only available technique for making this measurement. Later in this report and in subsequent papers, it will be demonstrated that reasonably good agreement is obtained between laboratory and in situ measurements made with known quantities of sulfuric acid vapor present in the test environment.

SECTION 6

RESULTS

FLY ASH CHARACTERIZATION

The results of the physical and chemical characterization are shown in Table I. The elemental chemical analysis results are expressed in weight percent as oxides. The loss on ignition value is listed separate from the total chemical analysis, because the analysis was conducted using an ignited specimen. Helium pycnometer density values are shown in grams/cc and are used to calculate resistivity specimen porosity. Bahco particle classifier results are shown as mass-median-diameter in microns. This value and the ash layer porosity can be used to calculate a crude value that is proportional to specific surface. The last column shows the location from which the ash sample was obtained.

Most of the elements determined in the chemical analysis show a wide variation in concentration among all the ashes. This reflects the attempt to acquire ashes produced from all ranks of coal acquired from all major coal producing areas in North America and some other regions. Density and mean particle size also varied greatly among the ash samples. It was hoped that this situation might eliminate data bias that could occur using ashes produced from coals of a restricted area or of limited characteristics.

RESISTIVITY DATA

Effect of Fly Ash Composition

For all the fly ashes described in Table I, the resistivity was determined between 80°C and 460°C using the baseline conditions and test procedure previously detailed. Baseline conditions included an ash layer voltage gradient of 2 kV/cm and 9 volume percent water vapor in the simulated flue gas.

The resistivity data were plotted on semi-logarithmic graph paper versus the reciprocal of the absolute temperature. Figure 1 illustrates the data obtained for ash number 105. The curve shown in this figure has the characteristic inverted V-shape. At the higher temperatures, the curve is linear in agree-

Table I. Chemical and Physical Characterization of Fly Ashes

Ash No.	Chemical Analysis In Weight Percent As Oxides														Helium Pycnometer Density gms/cc	Mass-Median Diameter Microns	Source of Ash Sample
	Li_2O	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3	Total	$SO_4^=$	LOI			
101	0.04	0.38	4.4	1.1	1.9	13.1	24.0	52.2	2.1	0.3	0.6	100.1	0.38	1.1	2.39	26	Storage silo
103	0.04	0.53	3.1	1.2	2.2	9.6	25.1	54.2	2.3	0.1	0.5	98.9	0.22	1.8	2.04	15	Inlet, hopper
104	0.04	0.35	3.8	1.6	1.5	11.1	25.9	51.6	1.7	0.3	0.3	98.2	0.24	4.0	2.73	7	Inlet, cyclone
105	0.05	0.66	2.9	1.2	3.1	10.5	24.1	51.4	2.7	0.3	1.2	98.1	0.62	2.3	2.32	13	Inlet, hopper
106	0.05	0.48	2.8	1.1	2.1	11.4	28.2	51.0	2.5	0.5	0.6	100.7	0.45	2.7	2.41	13	Inlet, hopper
107	0.02	0.30	0.8	2.2	9.6	3.9	17.1	61.5	2.5	1.2	1.2	100.3	0.50	0.3	2.48	24	Inlet, hopper
109	0.01	0.46	1.6	2.9	14.5	7.8	18.5	51.0	1.4	0.5	1.9	100.4	0.50	0.8	2.28	50	Inlet, hopper
110	0.01	3.20	0.7	1.2	15.6	5.2	22.9	45.9	1.4	0.2	1.3	97.6	0.34	0.4	2.19	10	Proportionate blend, hoppers
111	0.01	0.29	0.7	1.8	12.8	4.3	22.5	55.0	1.1	0.1	0.3	98.8	0.26	1.0	2.54	20	Mechanical collector
112	0.05	0.34	0.5	6.8	19.6	4.7	21.4	43.8	1.6	0.3	1.9	101.0	0.19	0.3	2.52	11	Proportionate blend, hoppers
113	0.01	1.85	0.6	1.9	9.1	5.4	23.4	51.2	5.5	0.8	0.4	100.2	0.37	0.3	2.03	35	Inlet, hopper
114	0.02	2.02	1.4	2.8	13.0	10.2	18.5	47.7	1.4	0.4	4.2	101.6	1.80	1.0	2.50	10	Unknown
115	0.03	1.85	1.4	3.0	13.7	9.8	17.3	47.2	1.4	0.3	3.2	99.2	1.14	1.1	2.43	10	Unknown
116	0.02	9.70	0.6	3.7	17.3	8.7	19.3	28.9	1.9	1.0	5.7	96.8	5.65	0.7	2.79	12	Hopper
117	0.01	2.27	2.8	1.1	2.6	19.2	18.3	52.0	1.9	0.4	1.0	101.3	0.55	6.1	2.67	14	Hopper
118	0.02	0.29	1.8	3.6	8.6	5.9	23.7	51.9	1.3	0.4	1.3	98.8	0.71	0.8	2.50	3	Proportionate blend, hoppers
121	0.03	1.38	1.1	0.9	5.2	4.3	23.4	58.5	1.7	0.3	0.7	97.5	0.30	1.6	2.15	38	Storage silo
123	0.03	0.47	2.7	1.0	4.7	19.3	19.5	50.4	1.6	0.3	1.5	101.5	0.58	1.2	2.63	16	Proportionate blend, hoppers
124	0.04	0.22	2.7	0.8	0.4	4.8	31.5	54.5	2.8	0.1	0.2	98.0	0.20	3.2	2.38	14	Unknown
125	0.06	0.32	3.6	1.3	1.2	8.8	27.6	54.0	2.3	0.5	0.3	100.0	0.29	1.9	2.59	6	Unknown
126	0.02	0.33	2.7	0.8	1.5	23.6	19.9	46.2	1.9	0.4	0.8	98.2	0.42	4.7	2.76	16	Inlet, cyclone
127	0.05	0.43	3.9	1.5	1.4	10.3	27.9	51.7	2.3	0.7	0.8	101.0	0.50	3.2	2.71	4	Unknown
128	0.01	8.52	1.0	5.9	23.3	10.6	10.0	27.6	0.7	0.1	11.0	98.7	8.93	1.0	2.99	6	Hopper
129	0.02	1.58	0.2	8.9	32.2	12.6	12.3	22.6	0.7	0.3	7.9	99.3	2.81	1.0	2.91	12	Hopper
131	0.04	0.55	1.7	1.2	4.3	5.1	23.7	59.7	2.0	0.3	0.8	99.4	0.45	5.0	2.65	11	Unknown
133	0.02	1.67	0.8	1.9	11.8	5.9	23.2	51.2	1.8	0.2	1.6	100.1	0.69	1.7	2.37	15	Unknown
134	0.04	0.29	2.7	1.0	1.8	15.3	22.1	50.7	2.1	0.3	0.5	96.8	0.35	1.1	2.58	12	Unknown
135	0.07	0.29	2.4	1.0	1.6	11.0	26.1	55.3	1.9	0.3	0.2	100.2	0.25	3.0	2.31	13	Inlet, hopper
137	0.04	0.45	3.1	2.1	4.6	8.2	26.0	52.9	2.2	0.2	0.5	100.3	0.50	0.4	2.49	19	Inlet, cyclone
138	0.06	0.24	2.2	0.8	1.2	11.7	30.0	50.9	1.5	0.4	0.4	99.4	0.28	3.1	2.78	4	Proportionate blend, hoppers
139	0.02	4.67	0.8	1.6	11.5	5.9	20.1	52.7	0.7	0.4	0.6	99.0	0.41	0.3	ND	13	Proportionate blend, hoppers
140	0.04	0.26	2.7	0.3	0.3	0.7	27.6	63.4	2.1	0.1	0.3	97.7	0.19	3.2	2.43	8	Proportionate blend, hoppers
141	0.02	0.36	0.9	1.1	0.8	7.3	26.3	58.3	1.9	0.1	0.2	97.3	0.12	4.9	2.26	13	Inlet, hopper
142	0.02	0.67	1.2	1.7	7.0	4.5	21.5	59.3	1.1	1.0	0.4	98.3	0.24	2.0	2.27	80	Unknown
143	0.01	1.13	0.7	4.0	22.7	4.8	21.6	38.8	1.9	1.4	1.7	98.7	0.83	0.1	2.54	7	Unknown

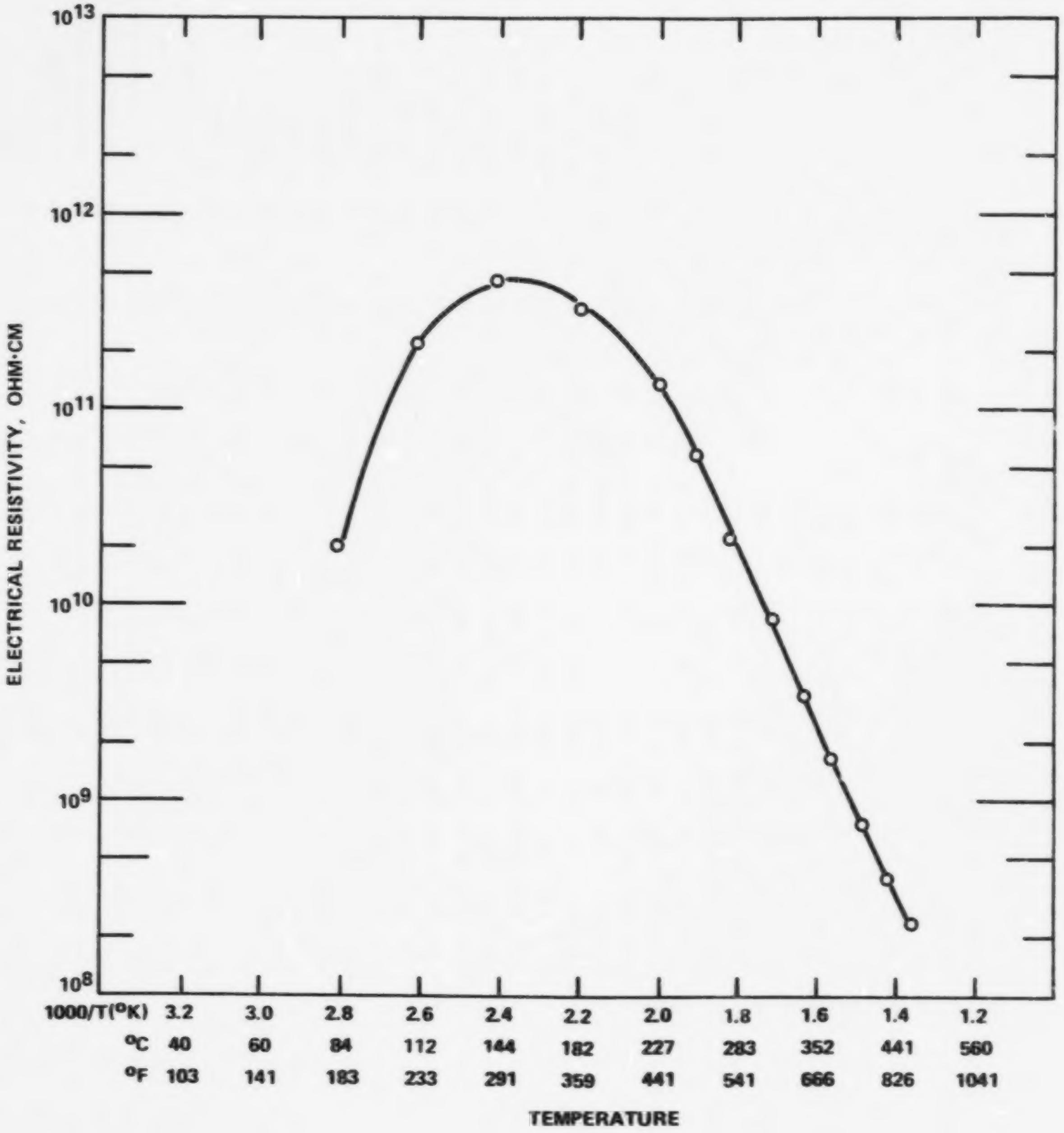


Figure 1. Typical resistivity-temperature data. Ash 105, baseline conditions.

ment with the Arrhenius equation for resistivity. From this part of the curve the experimental activation energy for volume or thermally controlled conduction can be calculated. As lower temperatures are approached, the curve departs from linearity due to the effect of surface conduction. After passing through a maximum, resistivity decreases rapidly with lower temperatures and concomitantly greater relative humidity.

After the data were plotted for each fly ash in this fashion, the resistivity values at specific reciprocal temperatures were selected, and the experimental activation energy was calculated. The resistivity data were compiled for 1000/T (°K) at 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, and 2.8. The experimental activation energy was calculated from the slope of the linear part of the resistivity curve using the logarithmic form of the Arrhenius equation:

$$\log \rho_v = \log \rho_{v_0} + [\theta/k \log e](1/T) \qquad (1)$$

where

ρ_v = volume resistivity,
ρ_{v_0} = a complex material parameter including the number of mobile charge carriers,
θ = experimental activation energy in electron volts,
k = Boltzmann constant, and
T = absolute temperature.

This information has been tabulated in Table II. In addition, the atomic percentages of lithium plus sodium, magnesium plus calcium, and iron are listed. These values were calculated from the compositional data in Table I. The weight percent values were normalized to 100 percent and converted to molecular percentages. The atomic percentage of cation was calculated by multiplying the molecular percentage of oxide by the decimal fraction of cation present in the oxide.

To examine the effect of ash composition on resistivity and to develop compositional information for the resistivity predictive procedure, the resistivity values listed in Table II were plotted versus the combined atomic concentrations of lithium and sodium. This was done, because it has been shown[8,9] that in the absence of sulfuric acid vapor the lithium and sodium ions are the principal charge carriers. Functioning as mobile ions, not oxide molecules, the number of charge carriers is proportional to the atomic concentration of these ions. Since the resistivity should be inversely proportional to the number of mobile charge carriers, log-log graph paper was used for these relationships.

Figures 2 through 7 show the measured fly ash resistivity values plotted as a function of the respective lithium plus sodium concentrations for the various reciprocal temperatures

Table II. Chemical, Physical and Electrical Characteristics of Fly Ashes

Ash No.	Atomic percentage			Measured Resistivity in ohm-cm at Various Temperatures						Experimental Activation Energy in Electron Volts	Ash Layer Porosity in %
	Mg+Ca	Fe	Li+Na	1000/T(°K) - 2.8 °C - 84 °F - 183	2.6 112 233	2.4 144 291	2.2 182 359	2.0 227 441	1.6 352 666		
101	2.3	2.5	0.37	6.0×10^{10}	6.2×10^{11}	1.0×10^{12}	6.0×10^{11}	1.4×10^{11}	2.9×10^{9}	0.90	54
103	2.5	1.8	0.49	3.4×10^{10}	4.2×10^{11}	9.0×10^{11}	5.8×10^{11}	1.4×10^{11}	2.6×10^{9}	0.90	50
104	2.5	2.1	0.35	8.8×10^{9}	1.5×10^{11}	4.0×10^{11}	4.0×10^{11}	1.5×10^{11}	3.6×10^{9}	0.79	69
105	3.2	2.0	0.62	2.2×10^{10}	2.5×10^{11}	5.0×10^{11}	3.5×10^{11}	1.3×10^{11}	2.5×10^{9}	0.86	59
106	2.4	2.1	0.47	3.0×10^{10}	3.5×10^{11}	6.5×10^{11}	4.5×10^{11}	1.4×10^{11}	2.6×10^{9}	0.90	59
107	7.5	0.6	0.24	1.3×10^{11}	1.3×10^{12}	2.3×10^{12}	1.9×10^{12}	1.0×10^{12}	5.2×10^{10}	0.86	47
109	11.2	1.3	0.35	3.4×10^{10}	2.6×10^{11}	7.4×10^{11}	8.5×10^{11}	4.8×10^{11}	2.4×10^{10}	0.79	44
110	10.8	0.9	2.43	1.7×10^{9}	1.2×10^{10}	2.3×10^{10}	2.8×10^{10}	2.2×10^{10}	3.5×10^{9}	0.83	60
111	9.3	0.7	0.23	2.2×10^{11}	1.8×10^{10}	3.3×10^{12}	2.7×10^{12}	1.1×10^{12}	5.0×10^{10}	0.83	54
112	16.8	0.8	0.31	3.2×10^{10}	2.8×10^{11}	8.0×10^{10}	1.2×10^{12}	1.0×10^{12}	1.1×10^{11}	0.83	59
113	7.3	0.9	1.40	2.0×10^{9}	1.5×10^{10}	3.9×10^{10}	4.6×10^{10}	3.0×10^{10}	1.8×10^{9}	0.66	55
114	10.3	1.7	1.52	2.7×10^{9}	1.8×10^{10}	4.0×10^{10}	4.6×10^{10}	3.0×10^{10}	2.2×10^{9}	0.68	64
115	11.0	1.7	1.43	4.5×10^{9}	3.4×10^{10}	9.0×10^{10}	9.6×10^{10}	6.5×10^{10}	4.7×10^{9}	0.74	60
116	14.4	1.6	7.53	1.0×10^{8}	6.5×10^{8}	1.4×10^{9}	1.8×10^{9}	1.7×10^{8}	9.0×10^{7}	1.10	67
117	2.7	3.6	1.84	3.3×10^{9}	3.2×10^{10}	4.6×10^{10}	2.2×10^{10}	4.5×10^{9}	8.0×10^{7}	0.86	58
118	8.4	1.0	0.25	8.0×10^{10}	7.6×10^{11}	1.4×10^{12}	1.1×10^{12}	5.2×10^{11}	1.5×10^{10}	0.95	70
121	4.0	0.8	1.10	7.5×10^{9}	6.0×10^{10}	8.4×10^{10}	5.5×10^{10}	1.8×10^{10}	5.1×10^{8}	0.79	53
123	4.1	3.6	0.43	5.0×10^{10}	6.5×10^{11}	1.2×10^{12}	5.5×10^{11}	1.3×10^{11}	2.2×10^{9}	0.90	63
124	1.0	0.9	0.24	2.0×10^{11}	3.0×10^{12}	5.3×10^{12}	3.2×10^{12}	6.8×10^{11}	9.5×10^{9}	0.90	67
125	2.0	1.6	0.35	8.0×10^{10}	9.2×10^{11}	1.8×10^{12}	9.5×10^{11}	2.3×10^{11}	3.8×10^{9}	0.95	65
126	1.9	4.8	0.33	3.8×10^{10}	5.0×10^{11}	9.2×10^{11}	4.6×10^{11}	1.1×10^{11}	2.0×10^{9}	0.90	56
127	2.3	1.9	0.42	3.7×10^{10}	3.8×10^{11}	9.0×10^{11}	5.8×10^{11}	1.9×10^{11}	2.7×10^{9}	0.95	81
128	19.0	1.8	6.20	1.4×10^{8}	1.0×10^{9}	1.6×10^{9}	2.0×10^{9}	2.0×10^{9}	1.0×10^{8}	1.32	78
129	26.3	2.1	1.16	2.2×10^{9}	1.2×10^{10}	2.8×10^{10}	3.9×10^{10}	2.8×10^{10}	2.8×10^{9}	0.86	68
131	3.7	0.9	0.48	2.2×10^{10}	2.6×10^{11}	6.8×10^{11}	5.2×10^{11}	1.9×10^{11}	3.2×10^{9}	0.83	76
133	8.9	1.0	1.27	2.6×10^{10}	2.2×10^{10}	4.5×10^{10}	4.5×10^{10}	3.4×10^{10}	3.4×10^{9}	0.76	54
134	2.2	3.0	0.31	3.8×10^{10}	4.2×10^{11}	7.6×10^{11}	4.4×10^{11}	1.1×10^{11}	1.8×10^{9}	0.79	56
135	2.0	2.0	0.34	4.0×10^{11}	2.2×10^{12}	2.9×10^{12}	1.2×10^{12}	2.8×10^{11}	4.0×10^{9}	0.90	67
137	3.8	1.5	0.41	1.4×10^{10}	1.3×10^{11}	3.2×10^{11}	2.9×10^{11}	1.1×10^{11}	3.1×10^{9}	0.86	53
138	1.6	2.2	0.30	1.6×10^{11}	1.8×10^{12}	3.0×10^{12}	1.8×10^{12}	4.9×10^{11}	6.4×10^{9}	0.90	68
139	8.4	1.0	3.47	7.0×10^{8}	4.8×10^{9}	9.4×10^{9}	9.5×10^{9}	5.8×10^{8}	4.3×10^{8}	0.60	ND
140	0.5	0.1	0.26	2.4×10^{11}	3.4×10^{12}	6.7×10^{12}	3.9×10^{12}	8.5×10^{11}	1.3×10^{10}	0.90	75
141	1.5	1.3	0.32	1.8×10^{11}	1.4×10^{12}	2.5×10^{12}	1.0×10^{12}	2.5×10^{11}	4.7×10^{9}	0.83	66
142	5.8	0.8	0.53	4.4×10^{10}	6.0×10^{11}	1.3×10^{12}	8.0×10^{11}	2.9×10^{11}	5.8×10^{3}	0.86	61
143	17.1	0.8	0.84	1.1×10^{10}	9.0×10^{10}	2.5×10^{11}	3.1×10^{11}	2.2×10^{10}	3.0×10^{10}	0.79	64

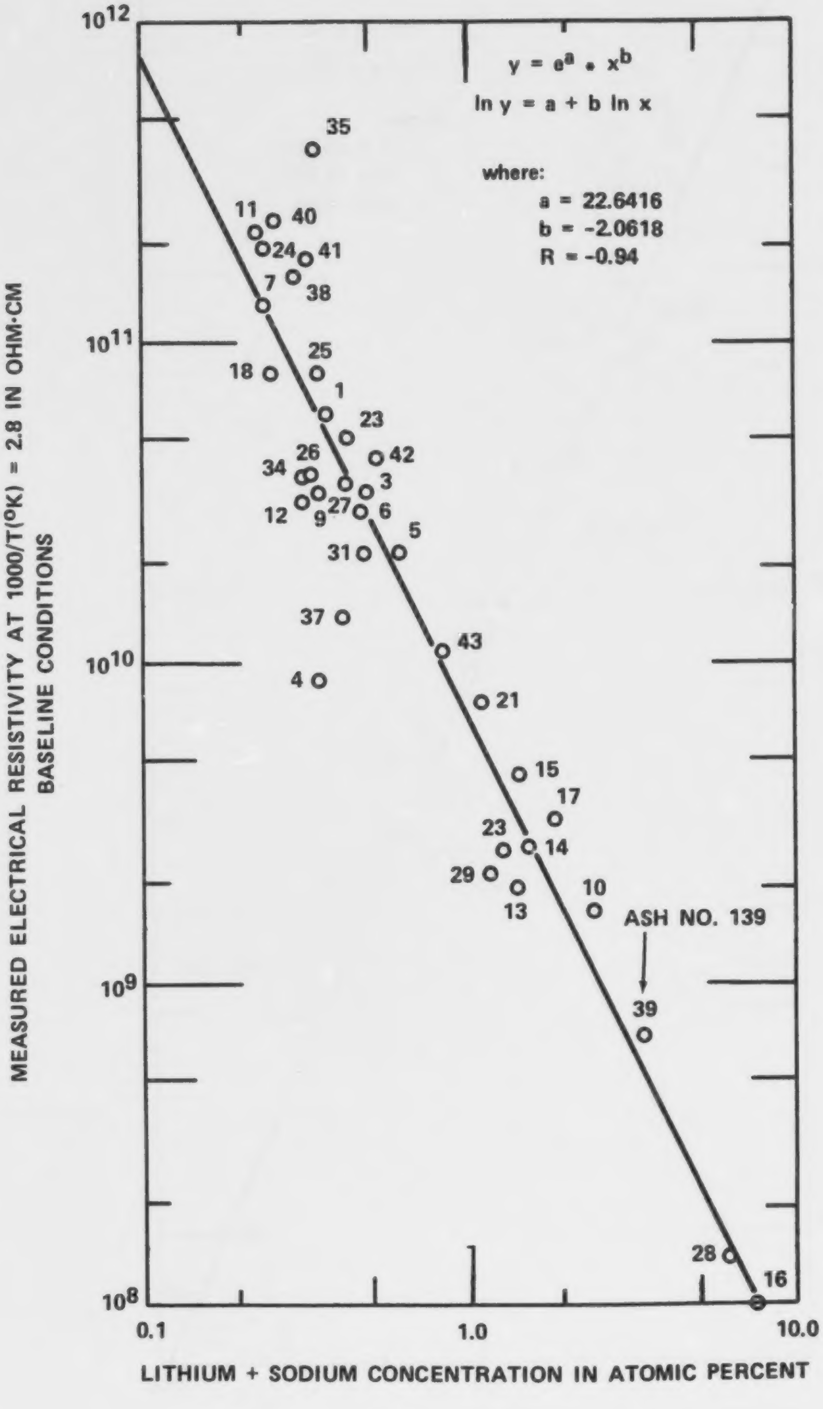


Figure 2. Resistivity versus lithium + sodium. Baseline conditions at 84°C.

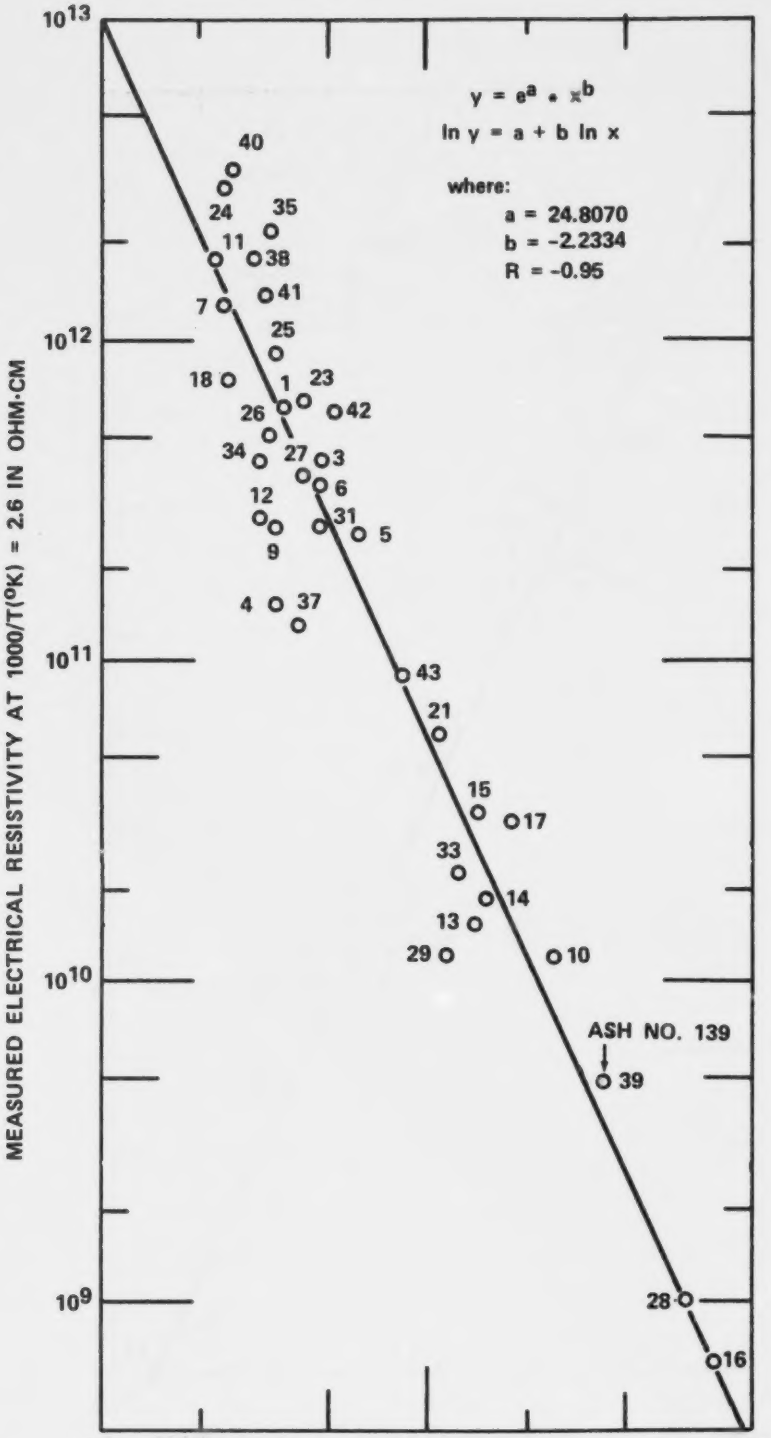


Figure 3. Resistivity versus lithium + sodium. Baseline conditions at 112°C.

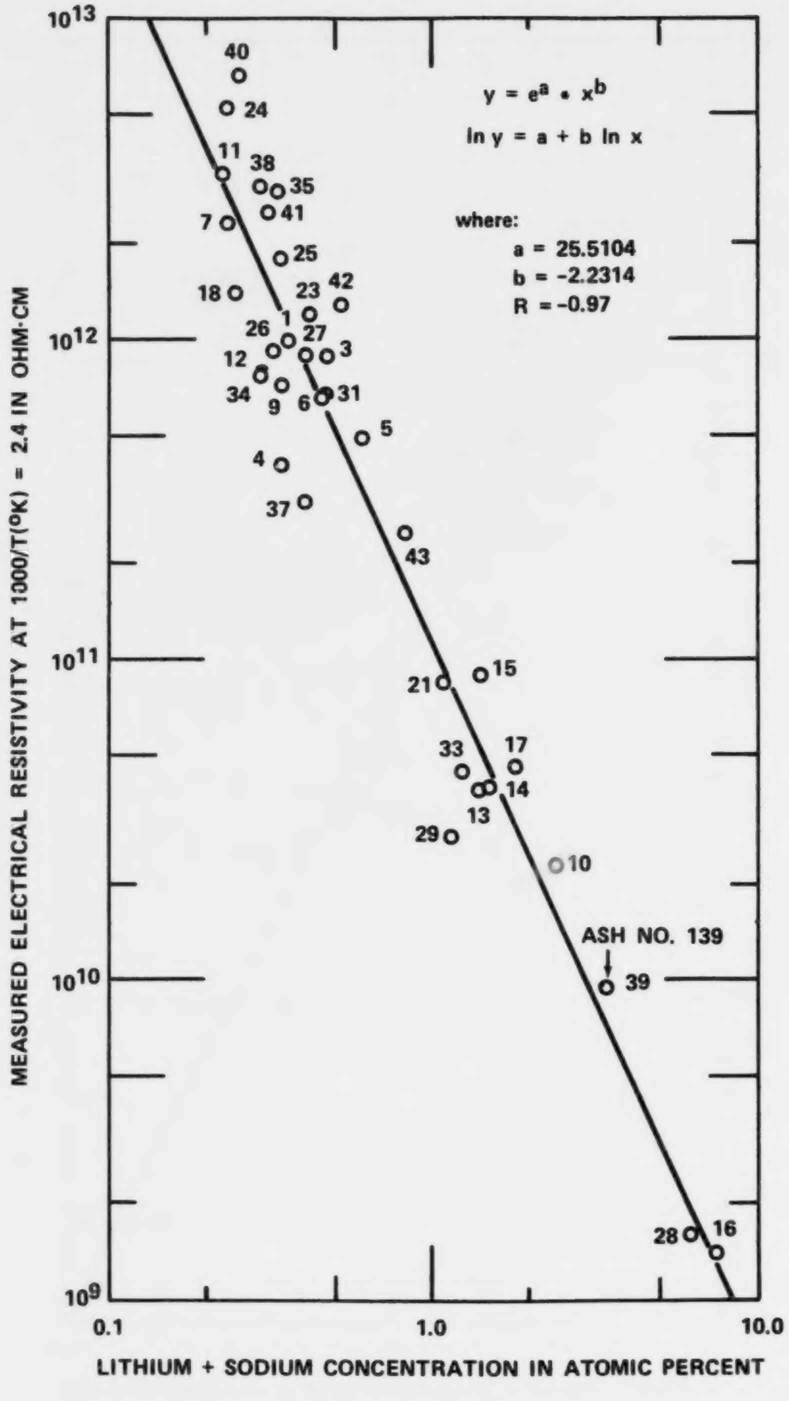


Figure 4. Resistivity versus lithium + sodium. Baseline conditions at 144°C.

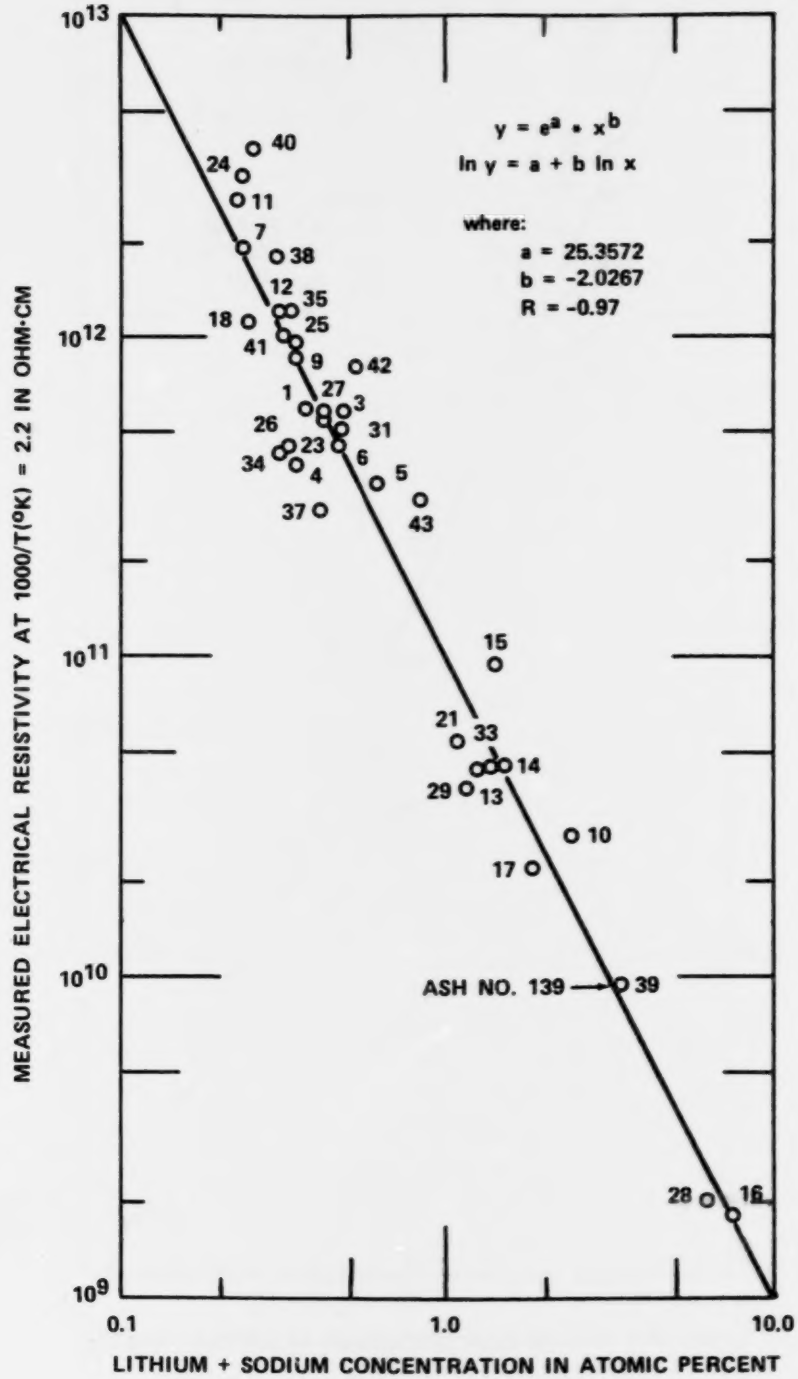


Figure 5. Resistivity versus lithium + sodium.
Baseline conditions at 182°C.

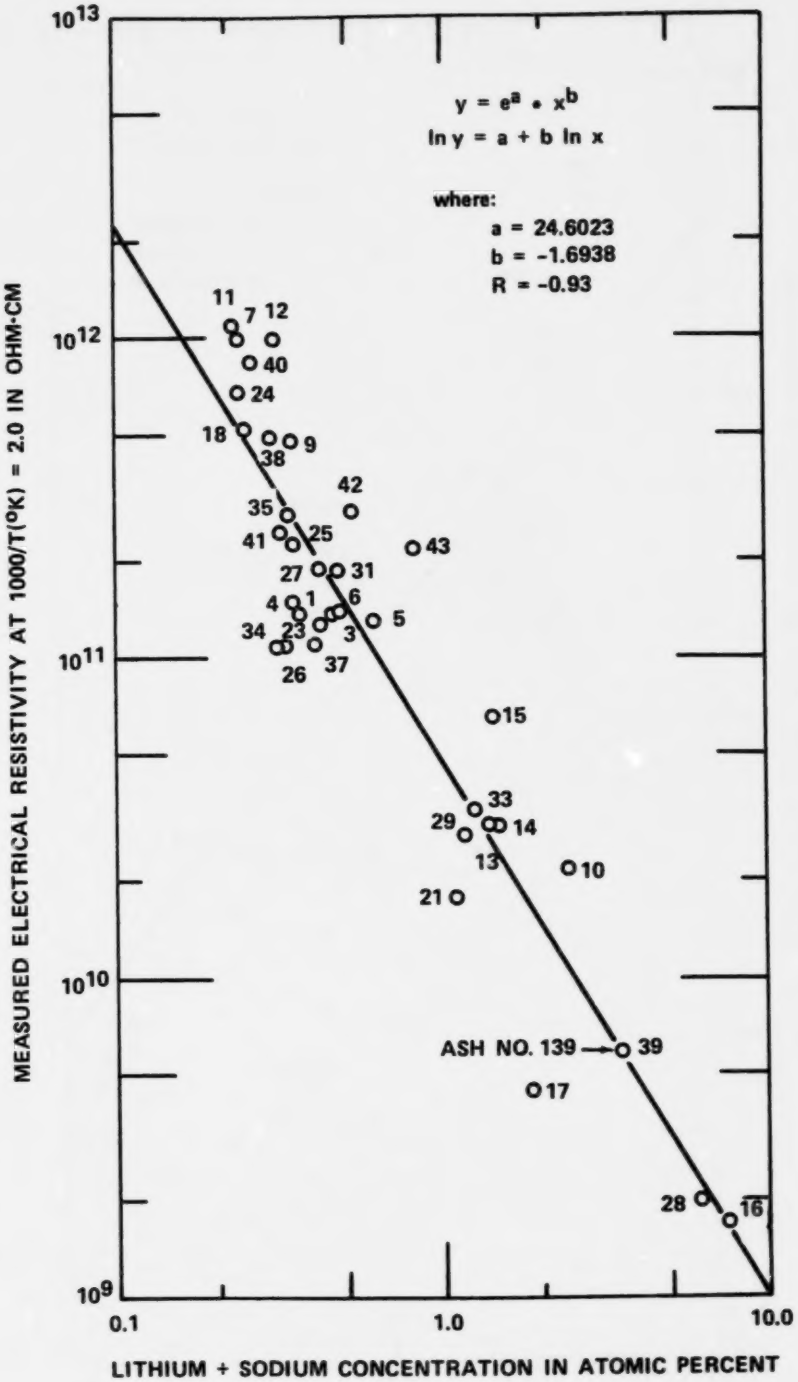


Figure 6. Resistivity versus lithium + sodium. Baseline conditions at 227°C.

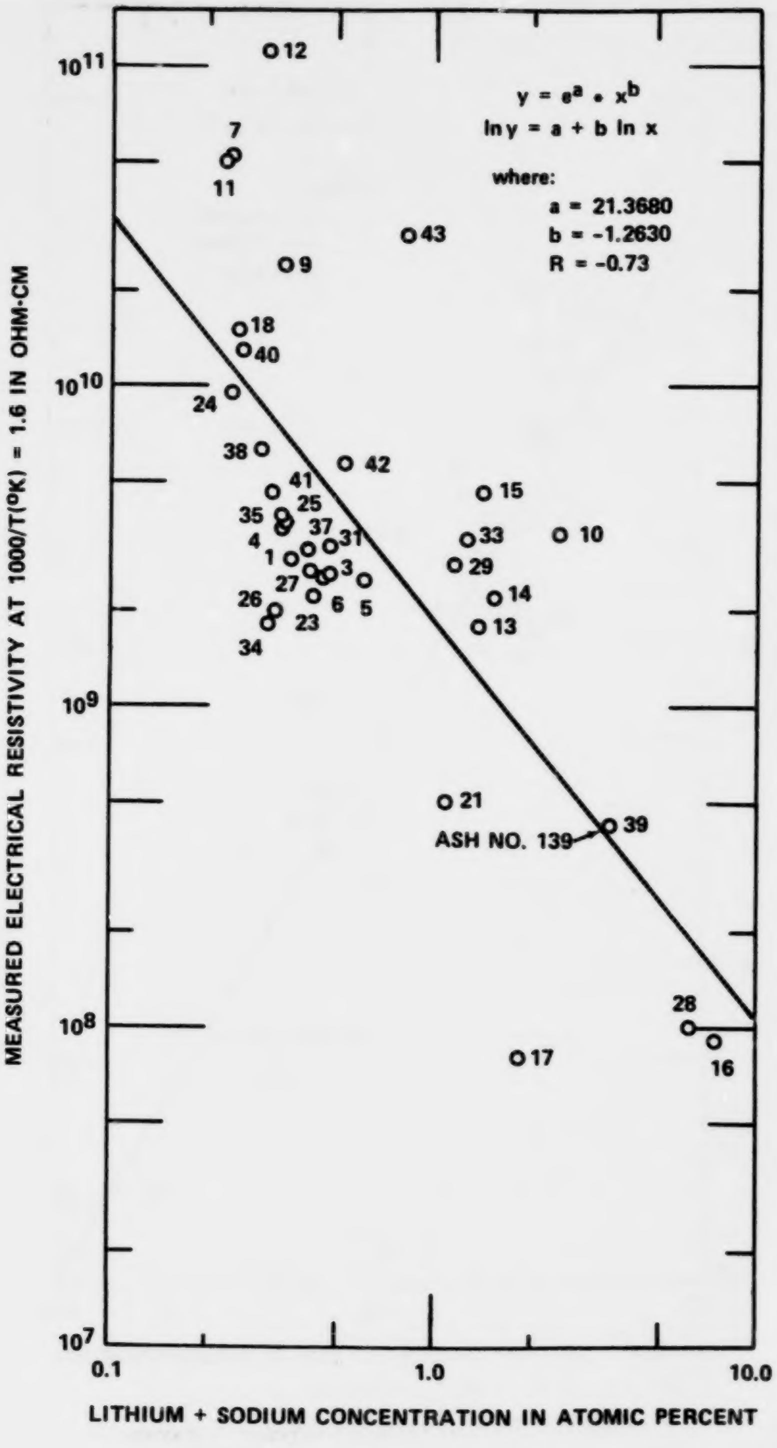


Figure 7. Resistivity versus lithium + sodium. Baseline conditions at 352°C.

of interest. A linear regression analysis was performed on each group of data, and the resultant line was superimposed on the data. On each graph the expression for the straight line is repeated, and the intercept and slope values are shown as well as the coefficient of correlation, R. This value is a measure of the degree with which the data fit the regression analysis, and a value of -1.00 would define perfect correlation between the two factors.

At the lower temperatures, 1000/T(°K) = 2.2 to 2.8 (359°F to 183°F), the plots typically show a negative slope of about 2.1 and a R value of -0.96. This indicates that under the prevailing test conditions the resistivity decreases two orders of magnitude for each order of magnitude increase in the combined concentration of lithium and sodium. The value of R suggests that a good correlation exists between these two factors.

In the simplest case, one can graphically predict resistivity from plots such as Figure 4 for 1000/T(°K) = 2.4 (144°C, 291°F) or calculate the value from the given equation. If the combined lithium plus sodium atomic percentage of an ash is 1.0 percent, the resistivity is 1.2×10^{11} ohm cm. This value, of course, is dependent on the quality of the laboratory measurement, is restricted to an environment containing 9 volume percent water and no sulfur trioxide, and relates to an ash under an applied voltage gradient of 2 kV/cm. Subsequently, it will be shown how the above predicted resistivity value can be changed to reflect other field strength levels and environmental conditions.

It would be convenient if the exercise just described could be repeated to predict the resistivity at all temperatures using the Figures 2 through 7. However, it is apparent that at the higher temperatures, where 1000/T(°K) = 2.0 or particularly 1.6, the relationship between resistivity and the combined atomic concentration of lithium and sodium degrades. This is apparent from the decrease in R values and the significant change in slope of the regression analysis curves.

These observations suggest that in the higher temperature range other ash compositional factors may influence the measured resistivity values. Previously investigators have shown that for certain ash types the concentration of iron[10] and the alkaline earth elements[11] (magnesium and calcium) affect resistivity. The measured resistivity data for 1000/T(°K) = 1.6 were examined with respect to these two compositional factors.

The as-measured resistivity data shown in Figure 7 were normalized to the values that would be expected if all ashes contained 0.4 atomic percent lithium plus sodium. This was done using an arbitrarily selected slope of -2.0, because the low temperature data indicated that the final slope would be approximately -2; see Figure 2. The Figure 7 resistivity values normalized to 0.4 atomic percent lithium plus sodium were plotted as a function of atomic percent iron to establish a correlation between resistivity and iron concentration for those ashes having a very limited range of magnesium plus calcium (1.9 to 2.7 atomic percent). Using this resistivity-iron correlation, the remaining Figure 7 resistivity values normalized to 0.4 atomic percent lithium plus sodium were also normalized to 1.0 atomic percent iron and then plotted to establish a correlation between resistivity and the atomic percentage of magnesium plus calcium. The correlations established between resistivity and iron concentration and between resistivity and the combined concentrations of magnesium and calcium allowed a secondary correlation to be established between resistivity and the combined lithium and sodium concentration for ashes normalized to constant values of 1.0 atomic percent iron and 2.5 atomic percent magnesium plus calcium.

This entire procedure was then reiterated to include the data normalized with respect to the alkaline earths for those ashes used to develop the initial resistivity-iron correlation. This extended the number of ashes that could be utilized in the correlation. Figure 8 shows the second iteration of the resistivity-iron correlation using those ashes having relatively low magnesium-calcium concentrations that are generally similar to ashes produced from coals of the Eastern United States. The linear regression analysis yielded a slope of -0.9696 and a coefficient of correlation of -0.88. Figure 9 shows the second iteration of the resistivity-calcium+magnesium correlation using those ashes that are generally similar to ashes produced from coals of the Western United States. The linear regression analysis yielded a slope of +1.2370 and a coefficient of correlation of +0.78.

Using the correlations shown in Figures 8 and 9, the resistivity data were normalized to 2.5 atomic percent magnesium plus calcium and 1.0 atomic percent iron. These data were then plotted as a function of lithium plus sodium concentration using a negative slope of about 1.7 obtained from the first iteration. The results are shown in Figure 10. Comparison of Figure 10 with Figure 7 shows the dramatic decrease in data scatter; R changed from -0.73 to -0.95, and the slope increased from -1.2630 to -1.8916. This indicates that the data scatter and seemingly lesser effect of lithium and sodium on resistivity at high temperatures as implied by Figure 7 was due to the wide variation in iron and alkaline earth concentrations. Furthermore, it is apparent that iron and the alkaline earths affect high temperature resistivity.

The linear regression analyses shown in Figures 8, 9, and 10 have been reproduced without the data points in Figure 11. The important characteristics of each curve are given. This

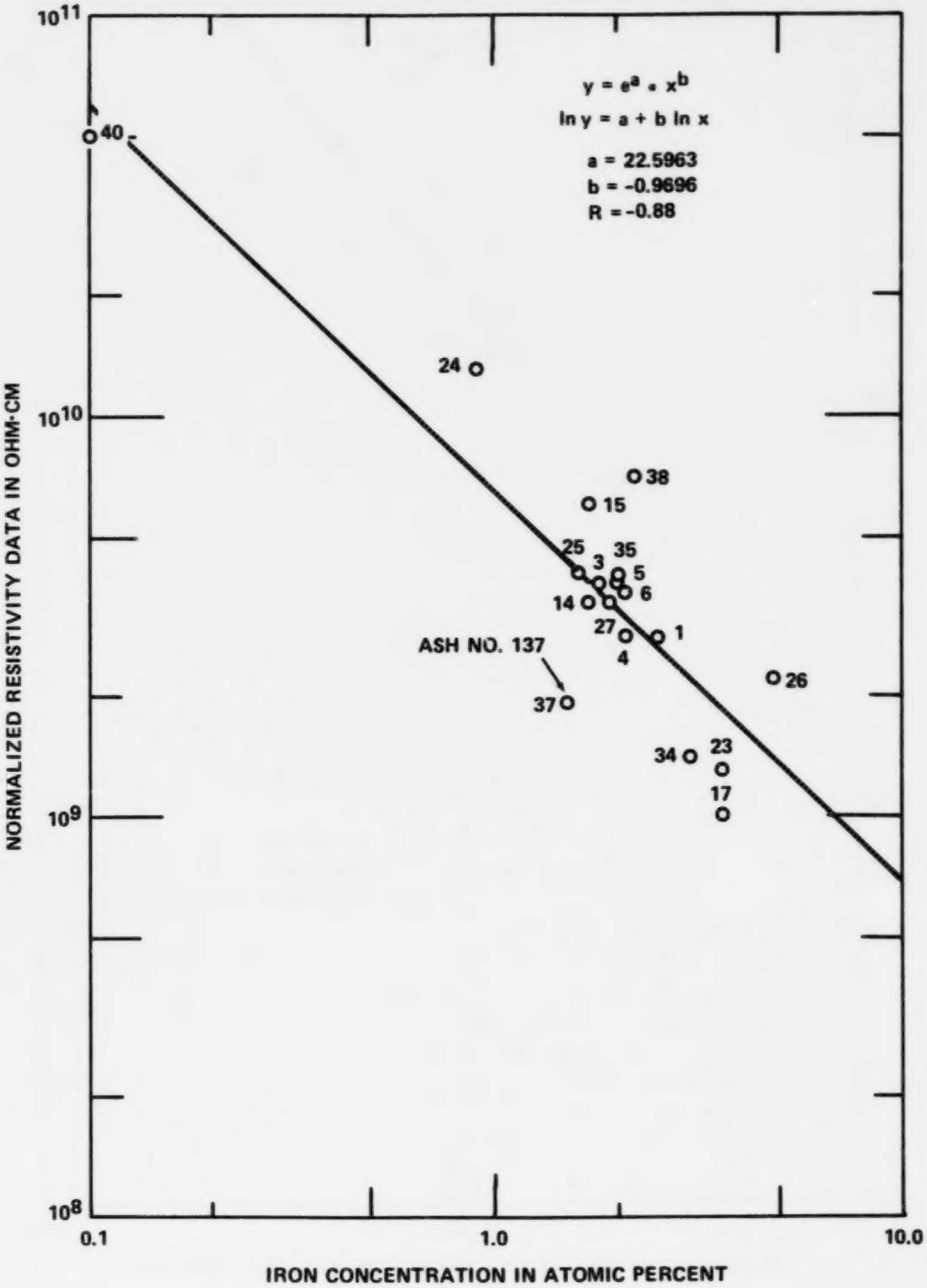


Figure 8. Second iteration of Figure 7 resistivity data. Normalized to 0.4% Li + Na and 2.5% Mg + Ca.

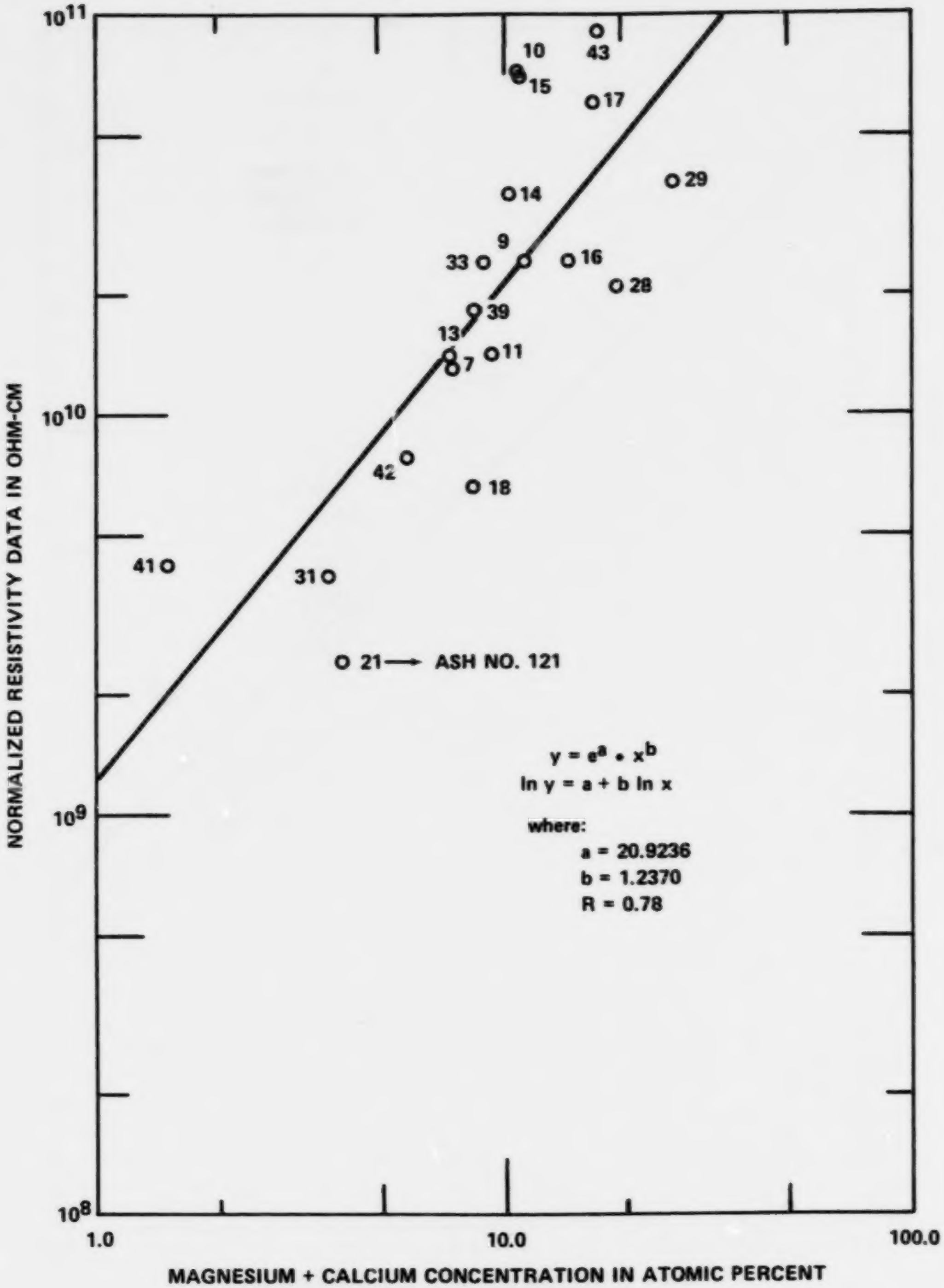


Figure 9. Second iteration of Figure 7 resistivity data. Normalized to 0.4% Li + Na and 1.0% Fe.

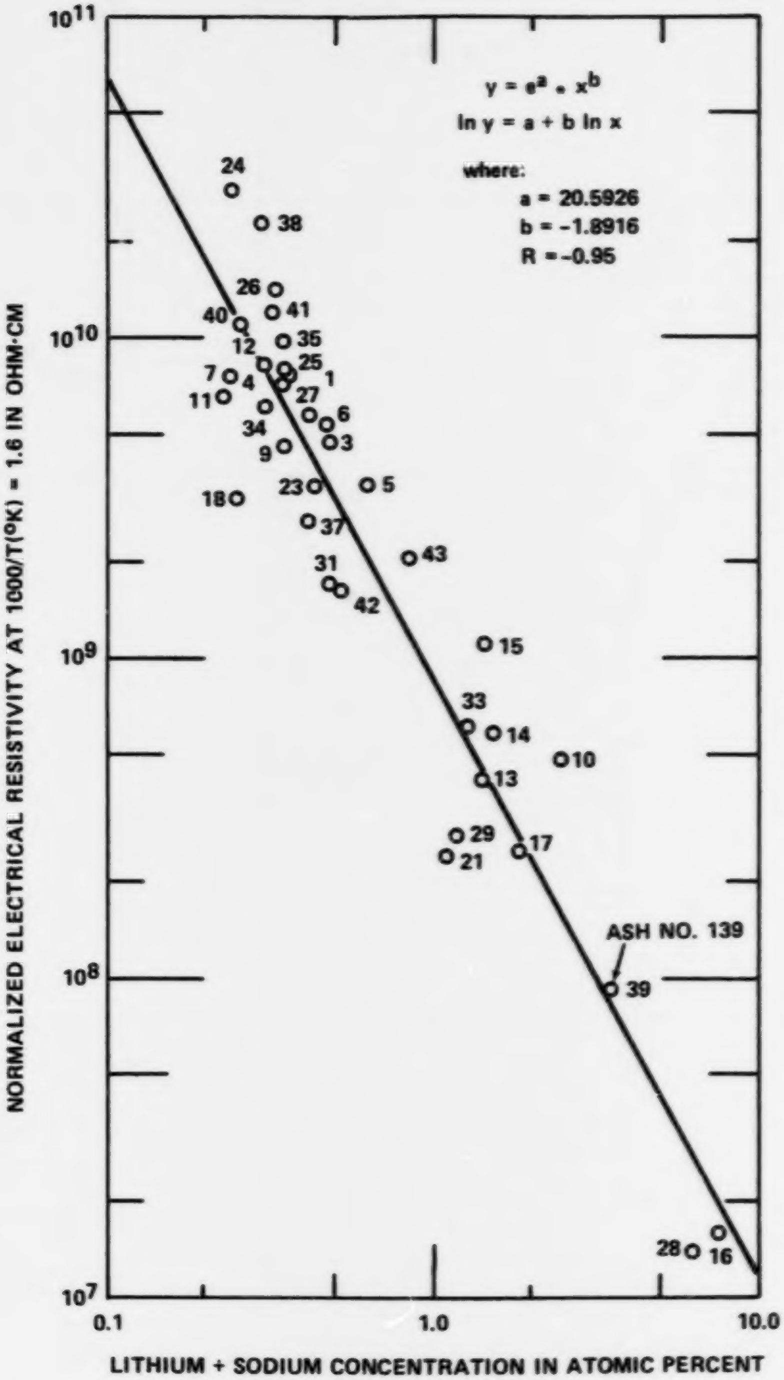


Figure 10. Resistivity versus lithium + sodium; baseline conditions at 352°C. Data normalized to 1.0% iron and 2.5% calcium + magnesium.

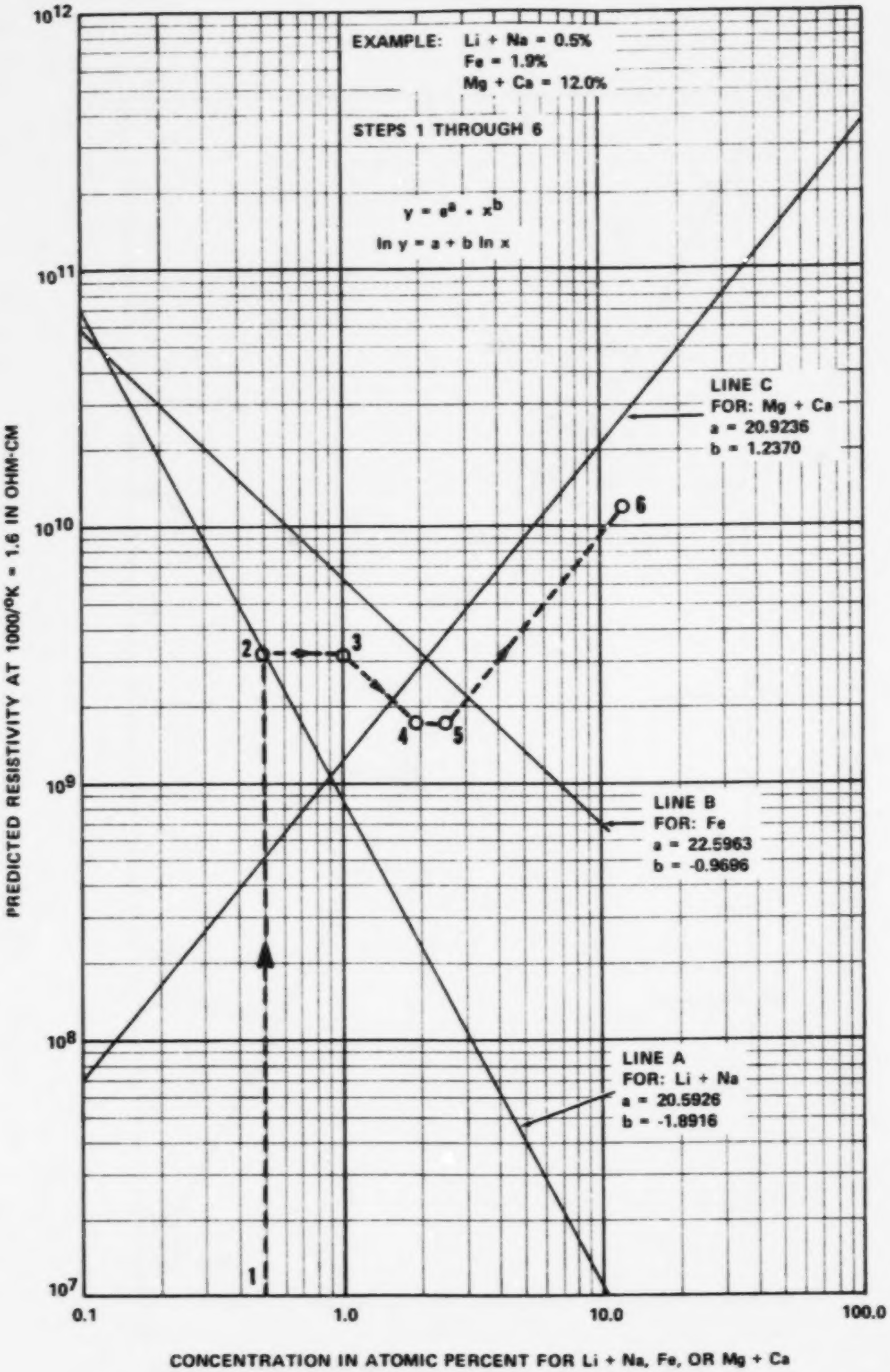


Figure 11. Predicted resistivity under baseline test conditions at 352°C as a function of the atomic percentage of lithium + sodium, iron and magnesium + calcium.

figure can be used to graphically determine the predicted resistivity for a reciprocal absolute temperature of (1000/°K) = 1.6 (352°C) and the previously described baseline test conditions. An example of this prediction is shown in the figure. The fictive fly ash example contains in atomic percentage: 0.5% lithium plus sodium, 1.9% iron and 12.0% magnesium plus calcium. Figure 11 is entered at point 1 using the atomic concentration of lithium plus sodium. At point 2, on Line A, it is indicated that a resistivity of 3.2×10^9 ohm cm would be expected if the fly ash contained 1.0 atomic percent iron and 2.5 atomic percent magnesium plus calcium. The resistivity value is translated laterally to point 3, 1.0 atomic percent iron. By moving from point 3 in a direction parallel to Line B to the assigned iron concentration at point 4, one finds the resistivity value, 1.7×10^9 ohm cm, for the fictive ash excluding the alkaline earth effect. By repeating the previous step, however, with respect to the combined concentration of magnesium and calcium (Line C), one arrives at point 6, 1.2×10^{10} ohm cm, the predicted resistivity for the ash composition and test conditions stated. It will be subsequently shown how this predicted value is adjusted for greater field strength and other temperatures.

Effect of Environmental Water Concentration

Sixteen ashes were selected from the large group available to examine the effect of water concentration on resistivity. The selection was made to have the widest possible variation in ash chemical composition. Each ash was evaluated with the previously described baseline resistivity test utilizing approximately 5, 9, and 14 volume percent water vapor in the environment. An example of the data acquired is shown in Figure 12 for ash #105.

For this particular ash, the effect of water vapor on resistivity was detected first at about 275°C and showed a maximum effect at the lowest test temperature. As the concentration of water increased, the maximum resistivity decreased and shifted to higher temperatures. These observations are similar to those made by other investigators.[12,13] For the example chosen, the high temperature data reproduced almost perfectly for the three tests. Because of the differences in porosity among tests of a single ash and the normal variation due to the precision of the resistivity measurement, this was not true for each set of three tests for all sixteen ashes examined. When data scatter occurred, the entire resistivity-temperature curve was shifted so that the three curves were superimposed in the high temperature region, where 1000/T(°K) = 1.6 to 1.4. The superimposed position was the average value for the three tests.

When the resistivity data presented in Figure 12 are plotted as a function of water concentration for various isotherms, a series of more-or-less straight lines result. Water concentra-

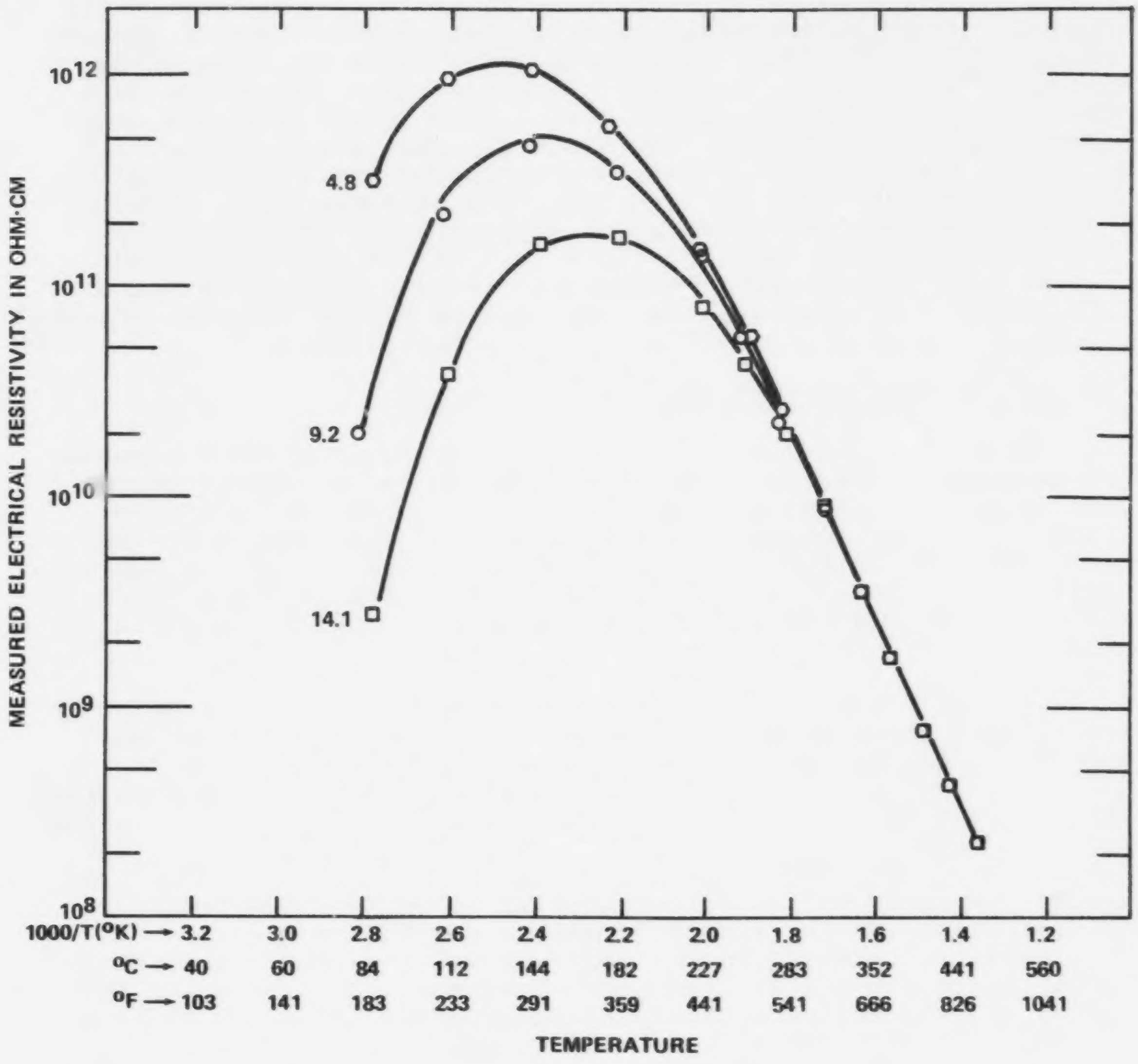


Figure 12. Resistivity as a function of water concentration for Ash No. 105.

tion can be expressed as relative humidity, partial pressure, or volume percentage as in the case of Figure 13. This figure shows the pronounced effect that environmental water concentration can have on fly ash resistivity especially at the lower, cold-side temperatures. At constant temperature and in an environment containing no sulfuric acid vapor, the surface conductivity of a specific fly ash is directly dependent on the interaction between the ash surface and the water vapor. Therefore, the linear relationship shown in Figure 13 is expected. Sixteen sets of data similar to those shown in Figure 13 were accumulated for the sixteen ashes used in this part of the investigation.

The slopes, S_w, of the curves such as those shown in Figure 13 were determined for each temperature of interest for each of the sixteen ashes utilized. From these data the average, maximum, and minimum slopes were plotted as a function of reciprocal absolute temperature as shown in Figure 14. Since $\bar{S}_w$ is a parameter defining the effect of environmental water concentration on resistivity, it is not surprising to find a linear relationship when this value is plotted on a logarithmic scale versus reciprocal absolute temperature. This relationship holds because a similar one exists for the relative humidity of a given absolute water concentration as a function of temperature. As the relative partial pressure of water vapor increases, the residence time of a water molecule on the ash surface increases.

The variation in S_w among ashes was not particularly great at temperatures lower than about 180°C (355°F). Above this temperature the effect of water vapor on resistivity becomes a minor consideration, and the variation between maximum and minimum values increases. In the high temperature region, the small effect seems sensitive to the affinity of a specific ash composition for water vapor. The minimum value of S_w at the highest temperature was zero.

The use of $\bar{S}_w$ is illustrated by the expression

$$\log \rho_s = \log \rho_{sb} + (C_w - C_b)\bar{S}_w \qquad (2)$$

where

$\log \rho_s$ = the logarithm of the surface resistivity for a specific lithium plus sodium concentration and water concentration, C_w;

$\log \rho_{sb}$ = the logarithm of the baseline surface resistivity for a specific lithium plus sodium concentration and a water concentration of 9 volume percent (values obtained from Figures 2-6);

C_w = the volume percent water concentration to which the resistivity is to be adjusted;

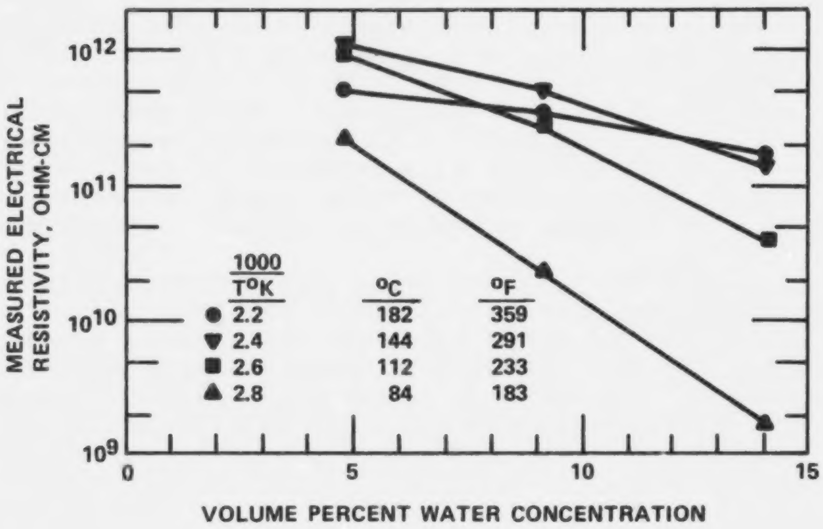


Figure 13. Resistivity as a function of environmental water concentration for various test temperatures, ash 105.

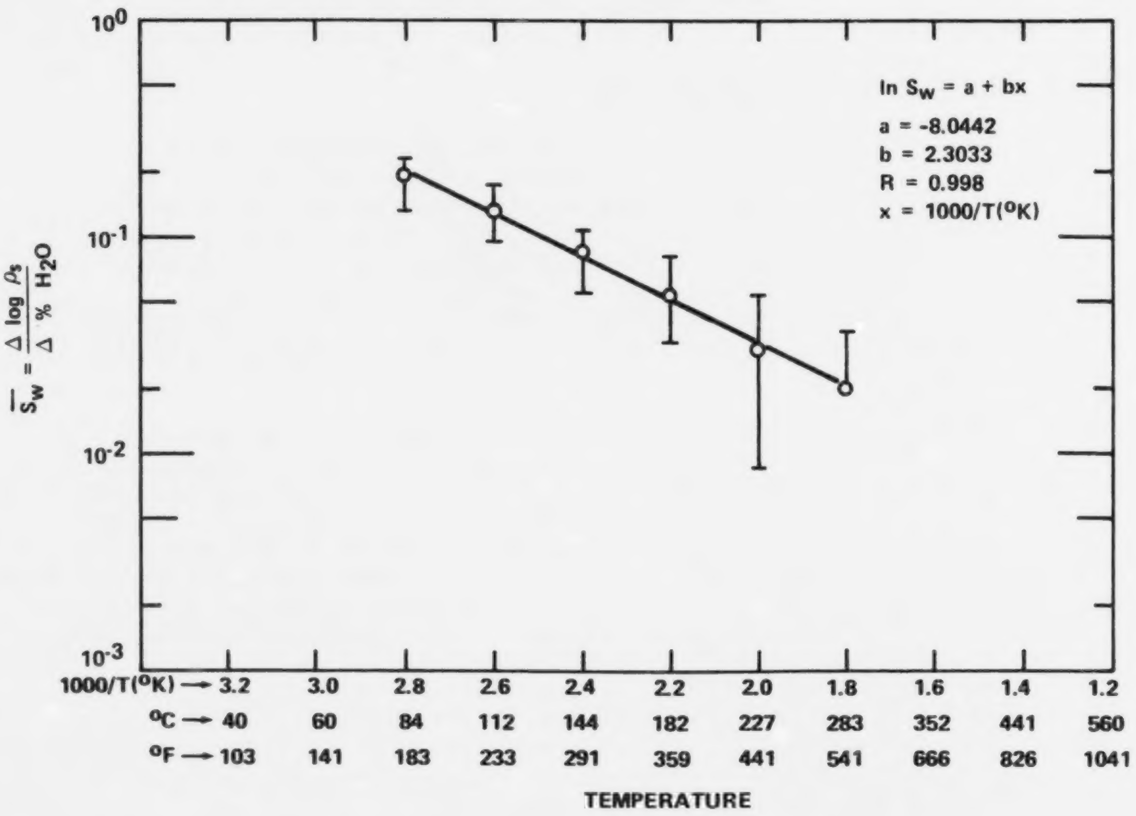


Figure 14. Effect of temperature on the resistivity-water concentration relationship, all ashes.

C_b = the water concentration used in establishing Figures 2-6, 9 volume percent; and

$\bar{S}_w$ = $\Delta \log \rho_s / \Delta \% H_2O$; for example, -0.0808 for $1000/T(°K) = 2.4$ and water concentrations between 5% and 15%.

After determining the resistivity for a given atomic percentage of lithium plus sodium in an environment containing 9% water vapor from Figures 2-6, the resistivity values for other water concentrations can be calculated from Equation 2, using values of $\bar{S}_w$ taken from Figure 14. If desired, a series of curves relating resistivity, water concentration, and temperature can be generated. The computer program for resistivity prediction described later in this report utilizes the expression shown in Figure 14.

Effect of Applied Electrical Stress

Since electrostatic precipitators are often operated at or near the point of dielectric breakdown of the ash layer, it is desirable to predict and/or measure fly ash resistivity at this electrical stress level. The ASME, PTC-28 suggests measuring laboratory resistivity at 90% of breakdown stress, and some *in situ* resistivity measurements are reported at about this point. However, a research program involving many fly ash specimens and a multiplicity of test conditions cannot readily comply with this procedure.

Resistivity as a function of applied electrical stress was determined for the selected sixteen fly ashes at one temperature (160°C) and one set of environmental conditions (9 volume percent water). Using an ash layer thickness of 6 mm, the applied voltage was increased until electrical failure occurred or a voltage gradient of 10 kV/cm was reached. Figure 15 shows the minimum, average, and maximum effect of increased voltage gradient on resistivity for the sixteen ashes tested. The data are expressed as relative resistivity plotted on a logarithmic scale versus applied voltage gradient. Relative resistivity was calculated as the ratio of the resistivity measured at some field strength, E, to the value obtained at 2 kV/cm, the baseline voltage gradient used in this work. Similar response of resistivity to applied voltage gradients has been found by others.[14]

The following algebraic expression was used to adjust resistivity values taken at conventional stress levels in the laboratory to reflect the effect of higher voltage gradients:

$$\log \rho_E = \log \rho_{E_2} + (E - E_b) S_e \qquad (3)$$

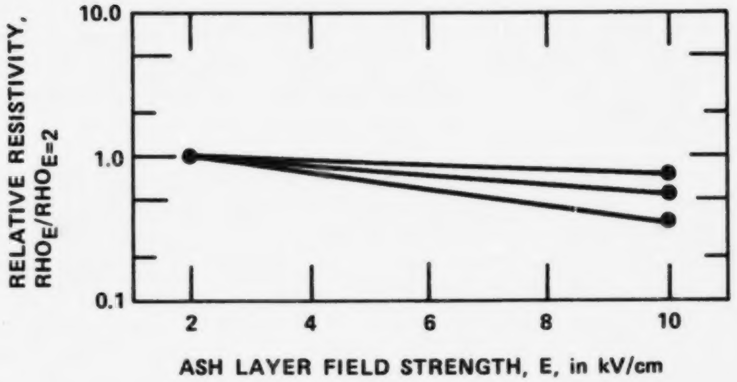


Figure 15. Relative resistivity values as a function of applied ash layer voltage gradient.

where

$\log \rho_E$ = the logarithm of resistivity adjusted to some field strength, E;

$\log \rho_{E_2}$ = the logarithm of resistivity with E = 2 kV/cm;

E = the applied voltage gradient to which log ρ_E is to be adjusted;

E_b = the applied voltage gradient used in establishing the base line data, 2 kV/cm; and

S_e = $\Delta \log \rho / \Delta E = -0.030$ (the average value for sixteen test ashes at 160°C and an applied voltage gradient range of 2 to 10 kV/cm).

Until additional information is available, the technique for predicting resistivity described in Section 7 will utilize the average S_e at all temperatures and test conditions and for all ash compositions. Unless otherwise noted, resistivity is predicted for E = 10 kV/cm only. That is, after the resistivity is predicted as a function of ash composition and water concentration at a voltage gradient of 2 kV/cm, it is adjusted to the value expected at 10 kV/cm. It is believed that in most cases this adjusted value will be equivalent to that determined at dielectric breakdown.

In the course of establishing a means of adjusting resistivity data taken at low stress levels to levels associated with precipitator operation, several interesting observations have been made. They are related below because they may affect thoughts pertaining to electrical breakdown. In the laboratory using ash layers about 6 mm thick, dielectric failure usually occurred at voltage gradients of 4 to 12 kV/cm. In situ field test determinations with a point-plane probe using the parallel plate mode of operation show dielectric failure generally happens between 8 and 20 kV/cm. The higher values found with the point-plane device probably are due to the relatively thin ash layer under test, typically 1 mm.

The observation that dielectric strength increases with decreasing specimen thickness is commonly noted with regard to glasses and ceramic dielectrics.[15] In this laboratory it has been shown that the ash layer field strength at dielectric failure increases significantly as the ash layer thickness is decreased. Figure 16 shows resistivity as a function of ash layer field strength for two identical ash specimens tested simultaneously. The only difference between the two tests was that one cell had an ash layer thickness of 0.70 cm while the other was 0.24 cm. The applied voltage to each cell was identical. Although the

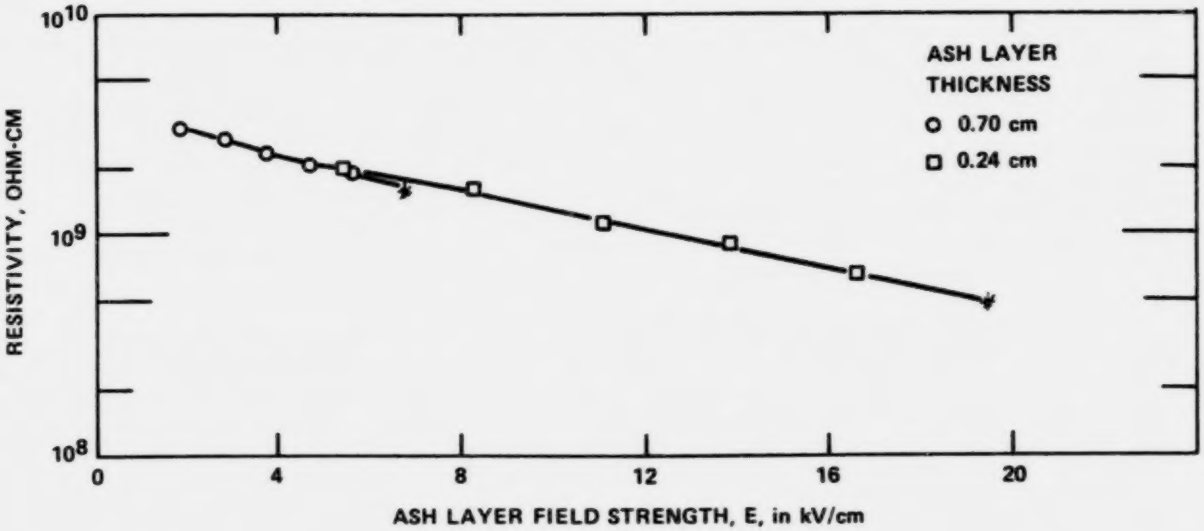


Figure 16. Resistivity as a function of field strength for ash layers of two thicknesses.

layers were of two significantly different thicknesses, dielectric failure occurred at the same applied voltage, 4.65 kV. Consequently it was recorded that the "spark", "arcing", or dielectric failure occurred at an average stress of 6.7 kV/cm and 19.6 kV/cm for the otherwise identical thick and thin specimens, respectively.

These data reaffirm the general observation that greater average electrical stress across an ash layer decreases the resistivity. This is probably a result of the increased number and/or the increased mobility of charge carrying ions. It is also suggested that average field strength has little effect on dielectric failure since the thick and thin specimens failed at the same voltage. Failure may have occurred at some location in the ash layer on the basis of a "weakest link" that is common to thick or thin specimens. Arguments can be presented that the failure is related to the fly ash itself or to the gas phase in the ash interstices.

Also it is interesting to note several manifestations of an ash layer dielectric failure during resistivity determinations. Figure 17A shows a resistivity test cell in the environmental test chamber with the upper electrode removed after a failure had occurred. The B view of this figure shows the lower, negative, cup electrode. Figure 18 shows the upper and lower electrodes after the removal of the ash. The evidence of arcing between these two electrodes is obvious and in proper register with the damaged ash layer.

Detailed examination of failure regions occurring during tests at 160°C provided the information schematically shown in Figure 19. Illustration number one shows the observed situation that suggests an explosion took place leaving a clean cavity. Illustration two, a cavity with fused ash at the surface, and illustration three, a column of fused ash, show the effect of a thermal excursion probably in excess of 1000°C. The mechanism of dielectric failure has not been studied in this investigation. However, the observations suggest that ohmic heating at particle interfaces may play a role.

Some of these observations suggest that the dielectric failure of fly ash layers is imperfectly understood and that additional research is desirable. A list of experimental parameters would include: ash particle size distribution, ash layer porosity, ash layer thickness, environmental composition and pressure, temperature, ash composition including combustibles, and test procedures.

Effect of Sulfur Trioxide

General Observations--

Experimental problems encountered in attempting to quantitatively determine the effect of sulfur trioxide on the resistivity of fly ash in the laboratory severely delayed the completion

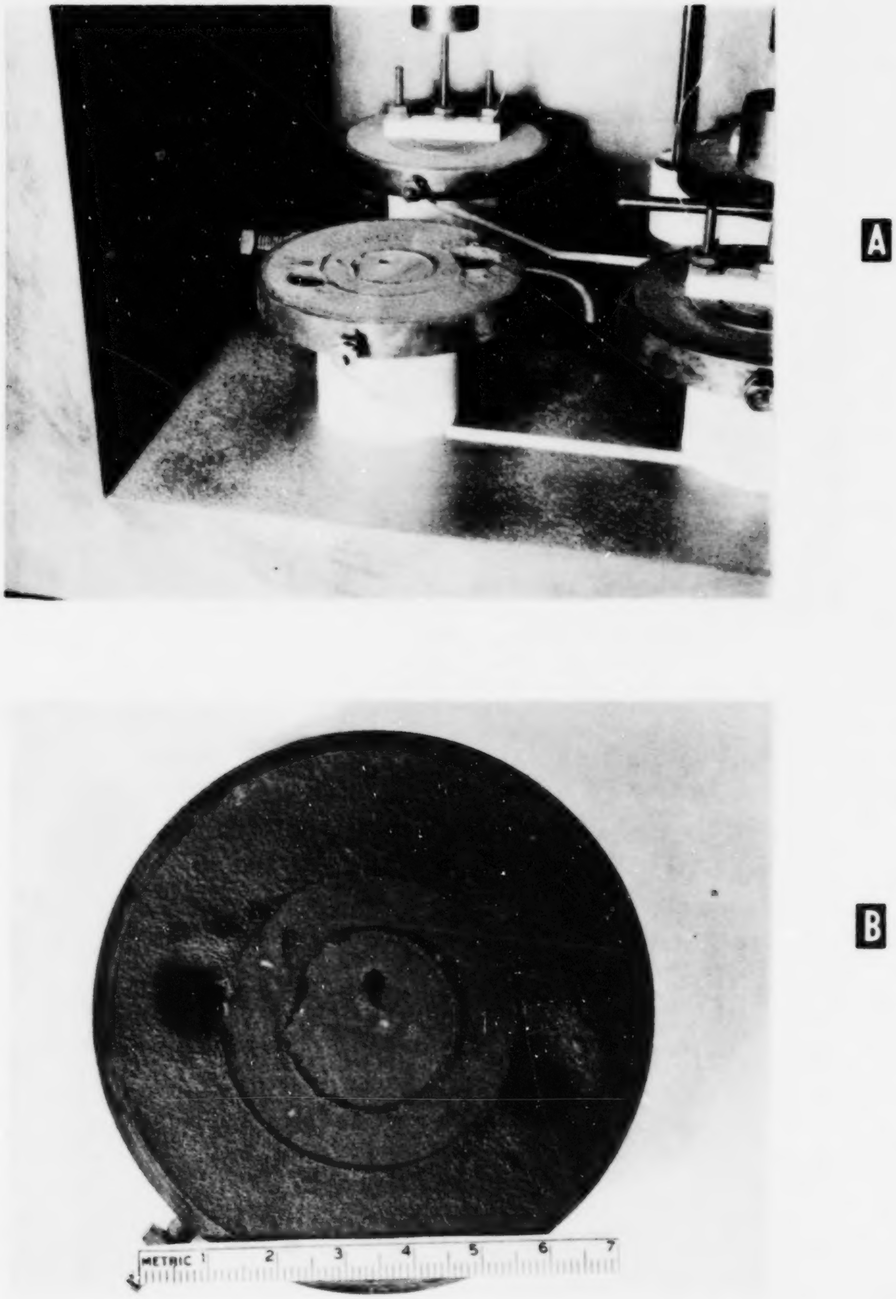

A
B
METRIC 1 2 3 4 5 6 7

Figure 17. Photographs of a resistivity test cell after dielectric failure.

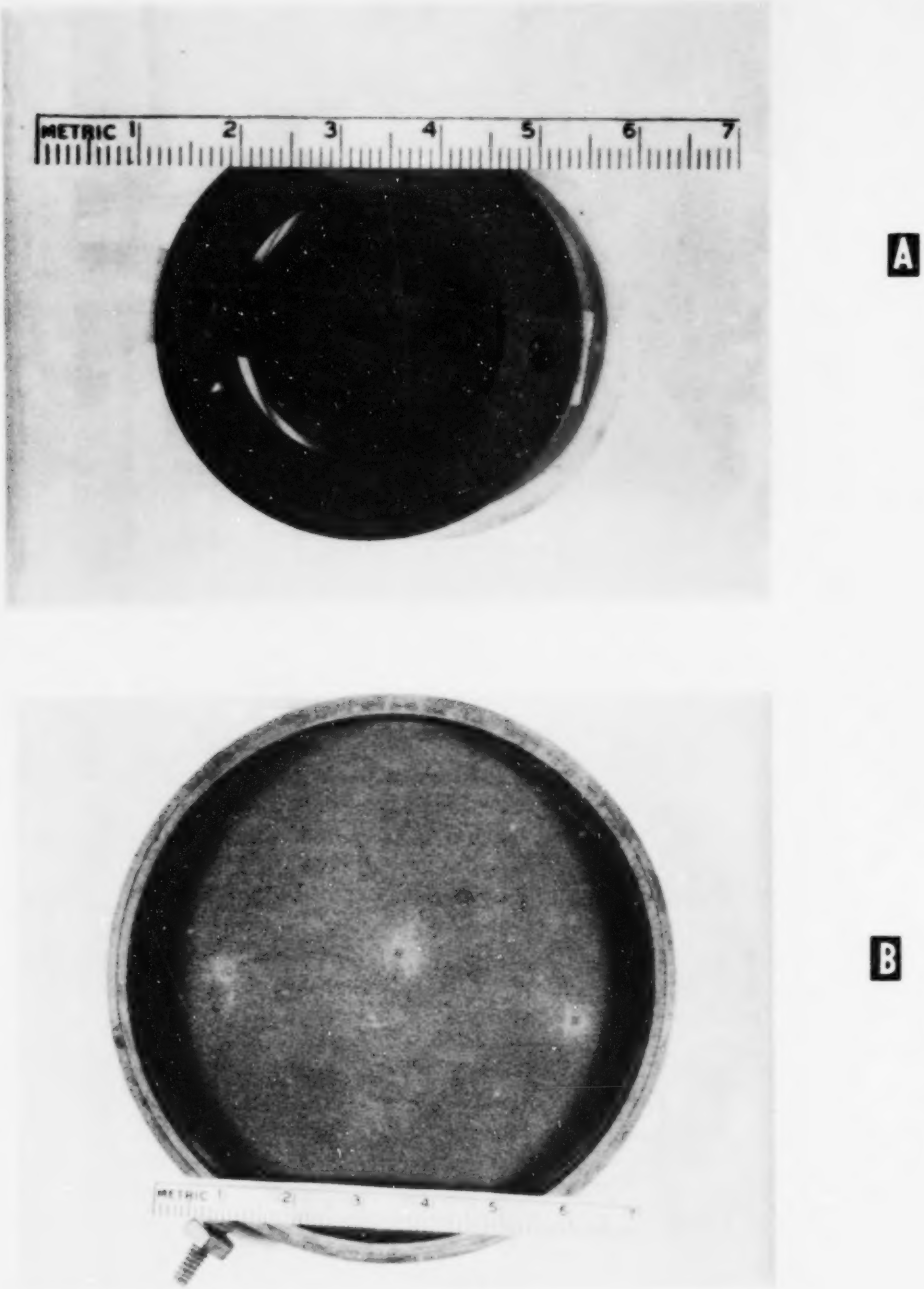
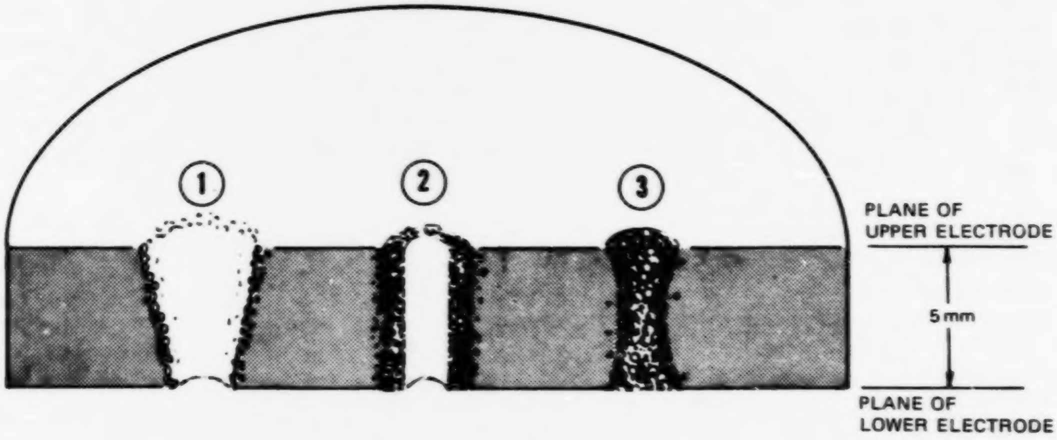

METRIC 1 2 3 4 5 6 7
A
B
METRIC 1 2 3 4 5 6 7

Figure 18. Photographs of the upper and lower electrodes from the test cell shown in Figure 17.


1
2
3
PLANE OF UPPER ELECTRODE
5 mm
PLANE OF LOWER ELECTRODE

1. OPEN CAVITY WITH "DRY" WALLS
2. OPEN CAVITY WITH "FUSED" WALLS
3. SOLID COLUMN OF "FUSED" PARTICLES

Figure 19. Schematic cross-section of cavities occurring in ash layers having experienced dielectric failure.

of this research project. The solution of the experimental difficulties has been previously discussed in Reference 6, in which the test equipment and procedure used with sulfur trioxide included in the environment is described. Because the time schedule was already significantly extended, only a few ashes were investigated with respect to the sulfur trioxide-resistivity relationship. The results were very interesting and demonstrated the pronounced effect the environmental sulfur trioxide concentration can have on the resistivity of fly ash. At this time it is obvious that the data base is small, and one should therefore use the quantitative information with cautious reserve. Under an Environmental Protection Agency grant, additional research will be conducted to expand this data base.

Experimentation using sulfur trioxide was somewhat different from the baseline work. In these experiments the fly ash under test was thermally equilibrated three hours in dry air at the temperature of interest. Resistivity was determined, water vapor was added to the environment, and resistivity was determined again. After the ash had equilibrated with the air-water environment, the desired concentration of sulfur trioxide was injected, and resistivity as a function of time was determined. Using the asymptotic approach of the resistivity to a minimum value as the end point, about an eighteen-hour exposure was required to equilibrate the ash volume under test with the sulfuric acid vapor in the environment.

Figure 20 shows a typical record of resistivity versus time of exposure to an environment consisting of air, 9 volume percent water, and 9 ppm of sulfur trioxide at 147°C. At time equal zero hours, the resistivity was 2×10^{13} ohm cm, and the water vapor was introduced. Within ten minutes the resistivity had decreased to 4×10^{10} ohm cm as the water vapor equilibrated with the ash. At time equal 0.5 hours the sulfur trioxide injection was started, and after about 1.5 to 2.0 hours, the resistivity started to decrease. After 16 to 18 hours of exposure, the resistivity asymptotically approached a minimum value of 2×10^{9} ohm cm. It apparently took this length of time for the sulfuric acid vapor to penetrate the ash layer (1 mm) and reach an "equilibrium" with the ash volume under test. At time equal nineteen hours the sulfur trioxide injection was stopped. The effect of the sulfuric acid immediately started to disappear and had essentially ceased within 2 to 3 hours after the injection was discontinued. The time required to eliminate the effect of the sulfuric acid is not related to the time required to remove the agent from the environment, because this apparatus allows for a 99% dilution of an environment in six minutes. The very rapid disappearance of the effect of sulfur trioxide when injection is stopped circumstantially suggests that the adsorbed sulfuric acid participates directly in the surface

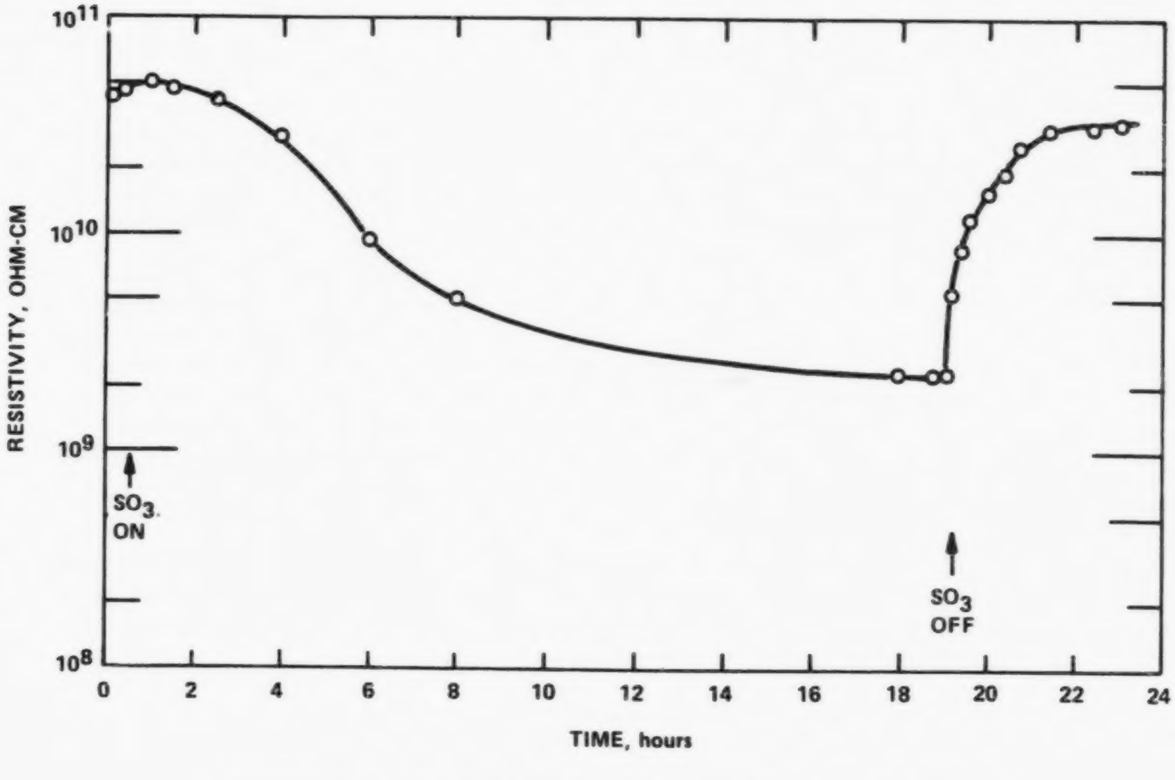


Figure 20. Resistivity-time after injection of 9 ppm sulfur trixoide in an environment of air containing 9% water.

conduction process. Since there is no lasting effect, one cannot equilibrate an ash with sulfuric acid vapor, stop the injection, and then measure the effect. Neither can one expect to measure the effect of adsorbed acid after removing an ash from a commercial facility for subsequent testing in a conventional laboratory device. Resistivity as a function of time for various levels of sulfur trioxide concentration has been previously demonstrated.[16]

Information such as that shown in Figure 20 was obtained for several fly ashes from eastern and western coals using three sulfur trioxide concentrations, three water concentrations, and several test temperatures. Typical data are shown in Figure 21 for ash #143. The upper curve for the entire test temperature spectrum (circular symbols) was obtained using a simulated flue gas containing 9 volume percent water and no sulfur trioxide. The four data points indicated by hexagonal symbols were taken from curves similar to that in Figure 20 and represent the minimum resistivity at four different temperatures using an environment containing air, 9 volume percent water, and 9 ppm sulfur trioxide. A dashed curve is drawn to link the data acquired in the presence of sulfur trioxide with the high temperature data obtained without this agent. The low temperature portion of the resistivity-temperature curve shows the dramatic effect adsorbed sulfuric acid has on fly ash resistivity. This ash was the only one examined at four temperatures for a given set of environmental conditions. These data suggest that, under the influence of sulfuric acid vapor, the logarithm of resistivity is a linear function of absolute reciprocal temperature. This observation is reasonable when sulfuric acid vapor provides the principal conduction mechanism and the temperature is above the acid vapor dew point. Under these conditions, the resistivity will be dependent on the amount of acid vapor adsorbed by the fly ash. For a specific fly ash, the amount of acid vapor adsorbed is a function of the ratio of the given acid vapor pressure to the saturated acid vapor pressure for a specific temperature. The logarithm of this ratio is also a linear function of reciprocal absolute temperature. Therefore with increasing reciprocal absolute temperature, the logarithm of the acid vapor pressure ratio increases linearly and the logarithm of the resistivity decreases linearly.

Comments on the Sulfuric Acid Conduction Mechanism--

In order to better interpret experimental observations regarding the effect of sulfuric acid vapor on fly ash resistivity, a chemical transference experiment was conducted in an environment including sulfuric acid vapor. The objective of this experiment was to determine whether the migration of any chemical species under the influence of an applied electrical stress could be detected. The detection of a mass transfer would offer help in developing an explanation of the electrical conduction mechanism.

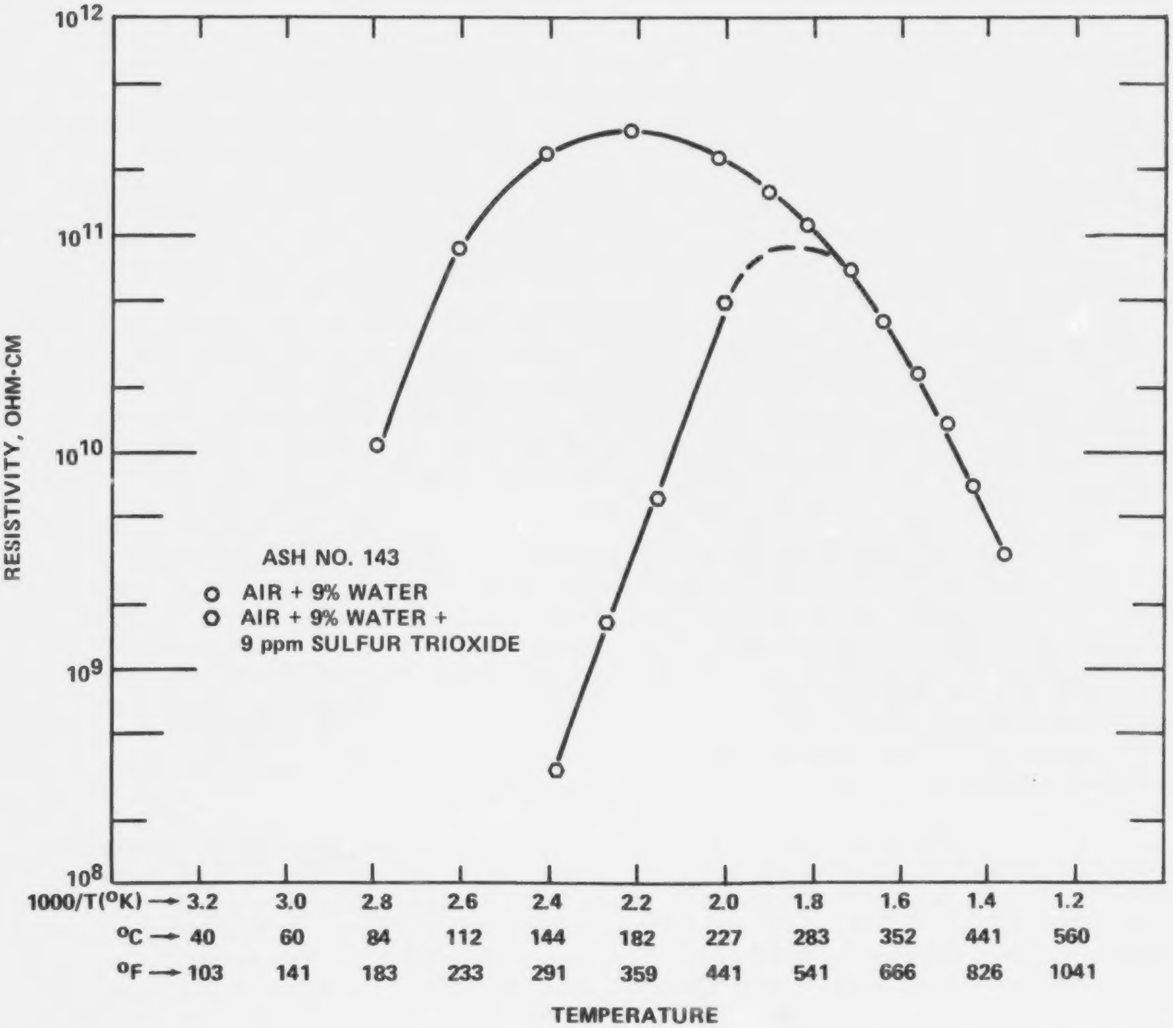


Figure 21. Resistivity-temperature relationship with and without sulfur trioxide injection.

A sample of ash was equilibrated in an air environment containing 9 volume percent water and 9 ppm sulfur trioxide at 140-150°C. Under these conditions, the specimen had a resistivity value of 1×10^8 ohm cm. A direct current voltage was continuously applied, and current was recorded as a function of time. After approximately 38 coulombs of electricity had been passed, the test was discontinued, and the volume of ash that had been under electrical stress was divided into thirds- the volumes contiguous to the anode and cathode, respectively, and the center volume. These specimens, as well as a specimen that had not been under test, were chemically analyzed. This information is shown in Table III.

The data reported as sodium oxide suggest that sodium ions migrate from the region of the anode to the volume of ash contiguous with the cathode. This qualitatively indicates that sodium participated in the conduction process as a charge carrier. Knowing the amount of electrical energy conducted during the experiment, 38 coulombs, and estimating the mass of ash involved, one can calculate the approximate concentration of sodium oxide that should be found in the ash volume contiguous with the cathode if only sodium were the charge-carrying species. This value is about 13% sodium oxide.

Since it was experimentally found that the sodium oxide concentration at the cathode was increased from about 3.2 to 3.8% instead of the calculated 13%, it can be concluded that sodium was only a minor participant in the conduction process. No other cation included in the chemical analysis showed evidence of migration.

It can be assumed that the sulfuric acid vapor adsorbed on the surface of the fly ash directly participated in the conduction process. The mechanism by which this occurs is not clear. It would seen unlikely that the large sulfate anion, $SO_4^=$, would be capable of migration. In fact, the data in Table III do not reflect an excess of $SO_4^=$ at the anode. This, however, does not preclude the participation of hydrogen ions in the charge transfer process. The mechanism of the charge transfer and means of maintaining electrostatic balance are unclear.

If the adsorbed acid vapor principally functioned by increasing the interparticle contact by capillary condensation,[17] one would expect an enhanced mass transfer of the normal charge carrying species, sodium, and an attenuation of current with increased time of continuously applied voltage. Neither of these occurred. Furthermore, one would not expect the almost instantaneous degradation of current carrying capacity when the sulfur trioxide injection is discontinued.

Table III.

Chemical Analysis of Ash Specimens Used in the Chemical Transference Experiment

Oxide	Specimen Not Tested	Test Specimen Contiguous with Anode	Test Specimen Center Section	Test Specimen Contiguous with Cathode
Li_2O	0.01 *	0.01	0.01	0.01
Na_2O	3.2	2.9	3.3	3.8
K_2O	0.7	0.8	0.7	0.8
MgO	1.2	1.2	1.1	1.1
CaO	15.1	14.6	15.1	14.7
Fe_2O_3	5.0	5.0	5.0	5.1
TiO_2	1.0	1.0	1.1	1.1
Soluble Sulfate				
$SO_4^=$	0.34	4.0	5.4	4.9

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*Expressed as weight percent of total sample.

In the transference experiment, the magnitude of current resulting from the applied voltage remained uniform from the beginning to the end of the test. This observation is consistent with the lack of evidence for significant chemical migration or transfer. If the principal source of conduction is a continuously supplied source of adsorbed sulfuric acid, one would not expect an attenuation of current with time as in the case when conduction is dependent on a finite concentration of mobile cations such as sodium ions. Under conditions involving simulated flue gas containing no sulfur oxides at both 150°C and 350°C when alkali metal ions are the principal charge carriers, the transference experiment current decreases with time, asymptotically approaching some minimum level. This decrease in current is caused by the depletion of carrier ions at the anode and excessive buildup of these ions at the cathode.

The results from the above-described chemical transference test offer strong evidence that the adsorption of sulfuric acid vapor on fly ash provides a separate and distinct conduction mechanism. The observations suggest that this mechanism is independent of fly ash composition, except with respect to the acid vapor-fly ash surface affinity. Certain other circumstantial evidence also supports the view that the adsorbed acid provides a separate mode of conduction. One such observation is the transient effectiveness of the sulfuric acid vapor illustrated in Figure 20. Even though the electrical stress was only applied intermittently, the effect of the acid vapor ceased quickly after injection was stopped, and the conduction process reverted to that provided by the mobile alkali metal ions. It has also been observed that the injection of 9 ppm sulfur trioxide resulted in resistivities of $1\text{-}5 \times 10^{8}$ ohm cm for two fly ashes having, respectively, resistivity values of 1×10^{10} ohm cm and 1×10^{12} ohm cm before injection. This indicates that the effect of the acid vapor adsorbed on the ash provides a conduction mode independent of that related to the interaction of water vapor and fly ash composition.

From the foregoing, it is visualized that under cold-side precipitator conditions two parallel conduction mechanisms are available. At very low concentrations of sulfuric acid vapor the electrical conduction in fly ash is principally influenced by the charge-carrying ability of the alkali metal ions as affected by the interaction of water vapor and the ash surface. At high concentrations of sulfuric acid vapor, perhaps 10 ppm in equilibrium with the ash, the conduction process is principally controlled by the adsorbed acid. At intermediate concentrations of acid vapor, both mechanisms contribute to the conduction process. Subsequently, the effect of environmental sulfur trioxide concentration on the predicted fly ash resistivity is incorporated by using the expression for calculating the resultant resistance for two or more parallel resistances. This allows the effect of both conduction modes to be appreciated.

Incorporation of the Environmental Sulfur Trioxide Concentration into the Resistivity Prediction--

Tests illustrating the effect of sulfur trioxide concentration on resistivity were principally conducted at 148-149°C ($1000/T(°K) = 2.37$) using an environment of air containing 9 volume percent water. The concentrations of sulfur trioxide injected were nominally 5 and 10 ppm. The data acquired under these conditions, using several fly ashes from eastern and western coals, are shown in Figure 22. The data points represent minimum resistivity values taken from curves such as the one shown in Figure 20 plotted against the measured concentration of condensable sulfuric acid vapor (expressed as sulfur trioxide in ppm) found in the test environment at the chamber outlet after the ash under test had been exposed for about eighteen hours.

Examination of Figure 22 shows the very pronounced effect sulfuric acid vapor has on resistivity and that fly ashes produced from western coals are affected to a greater degree than ashes from eastern coals for a given sulfur trioxide concentration. This observation can be justified on the basis of the generally more alkaline ashes from western coals having a greater affinity for the acid vapor.

An average value was calculated for each of the four data clusters, and straight lines were constructed connecting the data clusters for the eastern and western ashes, respectively. The following algebraic expressions define the constructed lines:

for eastern ash; where $Ca + Mg \leq 3.5\%$ or $K \geq 1.0\%$,

$$\log \rho_{a\ 1000/T(°K) = 2.37} = 12.9676 - (0.3075 \times \text{ppm } SO_3) \quad (4)$$

and for western ash; where $Ca + Mg > 3.5\%$ and $K < 1.0\%$,

$$\log \rho_{a\ 1000/T(°K) = 2.37} = 12.1612 - (0.3712 \times \text{ppm } SO_3). \quad (5)$$

There are obviously weaknesses in this proposition. It is possible that some of the resistivity values at the 5 ppm sulfur trioxide level are influenced by the inherent conduction related to the alkali metal ions. Also, one would expect the intercepts at zero sulfur trioxide to be the same value for each line in Figure 22. Acknowledging these shortcomings, it is believed that for an initial effort, these expressions can be used to predict the resistivity of fly ash as a function of the calculated concentration of sulfur trioxide in the environment.

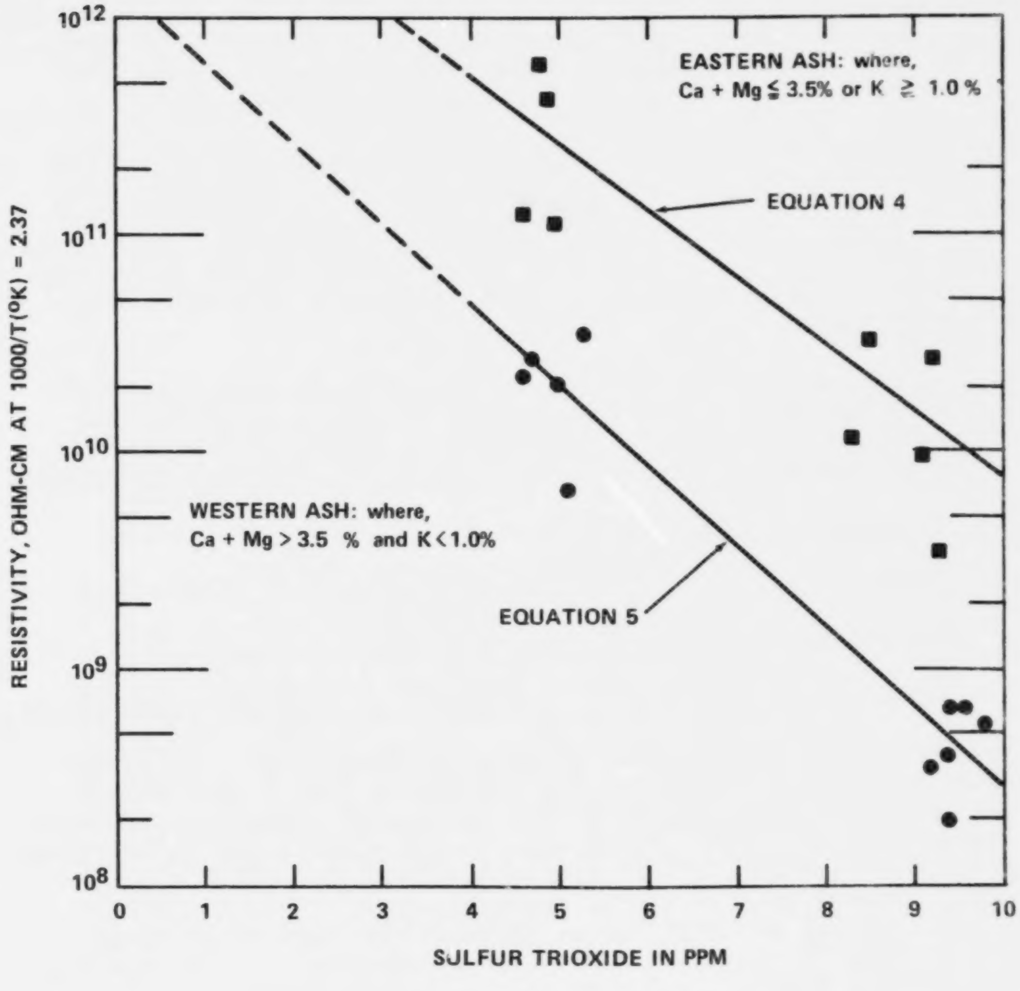


Figure 22. The effect of sulfur trioxide on resistivity at 1000/T(°K) = 2.37 in an air - 9% water environment.

Figure 22 and the expressions (4) and (5) are used to determine the resistivity of fly ash as a function of sulfur trioxide concentration at one temperature (1000/T(°K) = 2.37) and one water concentration (9 volume percent). To be able to predict resistivity based on the combined conduction modes due to the water vapor-ash composition interaction and due to the presence of adsorbed sulfuric acid vapor, one needs to know the effect on resistivity of the sulfuric acid vapor as a function of temperature. A few isothermal resistivity tests were conducted at several temperatures using a constant environment consisting of air, 9 volume percent water, and 9 ppm sulfur trioxide. These data are presented in Figure 23.

It is again apparent that for a given set of conditions the resistivity as influenced by the adsorption of sulfuric acid vapor is attenuated to a greater degree for ashes from western coals. Since several of the western and eastern ashes were very similar with respect to physical characteristics, it is suggested that this effect is related to the greater chemical affinity of the more alkaline western ashes for the acid vapor.

Figure 23 exhibits the very pronounced dependency of the sulfuric acid conduction mode on temperature. It was previously suggested that the observed linear positive relationship between resistivity and temperature is a reflection of the linear, negative relationship between the relative partial pressure of sulfuric acid vapor and temperature. With respect to the sulfuric acid conduction mode, the resistivities of the eastern ashes are particularly sensitive to temperature. This sensitivity is great enough that temperature gradients commonly found within a precipitator can cause one region to perform satisfactorily while another region demonstrates poor performance.

The difference in the slope of log ρ versus 1000/T(°K) curves shown in Figure 23 could be related to differences in adsorption energy as a function of variation in ash composition or to the position of the acid vapor dew point. For the test conditions used, the dew point was about 1000/T(°K) = 2.45 (270°F). At the dew point, homogeneous condensation occurs and other factors are no longer of great influence. One would expect resistivity to dramatically decrease as the dew point is reached. In Figure 23, it appears that the curves are converging at the dew point.

In a few experiments involving sulfur trioxide, water concentration was the variable. Ashes from both eastern and western coals were subjected to tests in which the injected concentration of sulfur trioxide, as well as all other factors, were constant while the water concentration was varied: 5, 9, and 15 volume percent. Although water concentration influences the relative

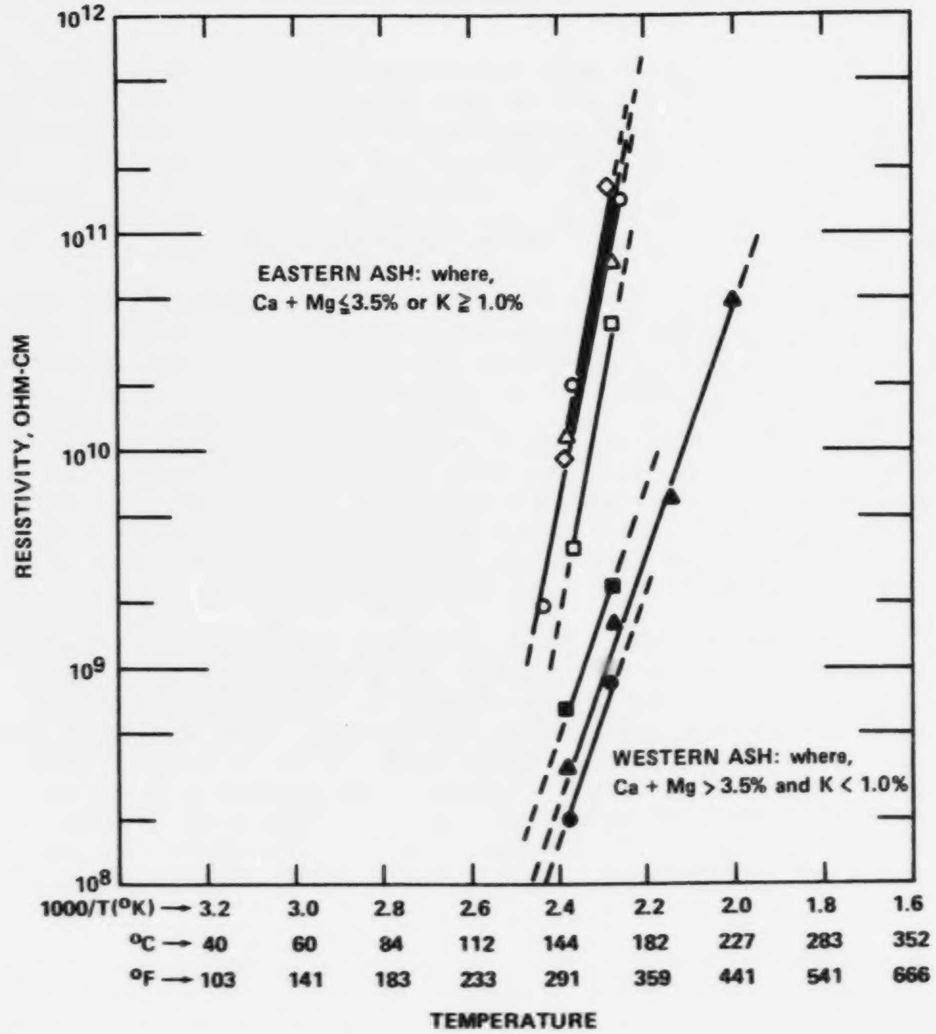


Figure 23. Resistivity versus reciprocal absolute temperature in an environment of air containing ~ 9 ppm sulfur trioxide and 9% water.

partial pressure of the sulfuric acid vapor, increasing the water concentration had no effect on resistivity. The value was apparently dependent only on the concentration of sulfur trioxide. As water concentration increases, the relative partial pressure of sulfuric acid vapor increases. This should cause an increase in adsorption and a decrease in resistivity. It is possible that for the specific experimental conditions used, the amount of vapor adsorbed as a function of relative partial pressure lies on a plateau of the adsorption-relative partial pressure curve. This possibility has been explicitly defined in sorption studies[18] involving fly ash and sulfur trioxide.

With respect to the principal objective of this research, the prediction of resistivity, both slopes shown in Figure 23 are utilized. After determining the resistivity at 1000/T(°K) = 2.37 for the specific sulfur trioxide concentration of interest using Equations (4) and (5), the line defining resistivity as a function of temperature is established using the following expression:

$$\log \rho_{a\ 1000/T} = \log_{a\ 1000/T\ =\ 2.37} + [S_a\ (2.37 - 1000/T)] \qquad (6)$$

where

$\log \rho_{a\ 1000/T}$ = logarithm of resistivity for a specific sulfur trioxide concentration and a selected value of 1000/T(°K);

$\log \rho_{a\ 1000/T\ =\ 2.37}$ = value calculated from Equation (4) or (5) for a specific sulfur trioxide concentration, ash composition, and a reciprocal absolute temperature of 1000/T(°K) = 2.37; and

S_a = slope of log ρ_a versus 1000/T(°K) = 10.1048 for ashes in which Ca + Mg $\leq$ 3.5% or K $\geq$ 1.0% and 5.6673 for ashes in which Ca + Mg > 3.5% and K < 1.0%.

T = temperature in degrees Kelvin

Expression (6) yields a curve of predicted resistivity as a function of temperature based on the estimated sulfur trioxide concentration in the flue gas and the chemically defined type of fly ash. It has been previously pointed out that the evidence suggests that conduction due to adsorbed sulfuric acid vapor is totally independent of other mechanisms. Also, in the absence of sulfur trioxide, it is known that conduction is dependent on the charge-carrying capability of the alkali metal ions and is controlled by the interaction of water vapor and the fly ash surface. Obviously, under certain conditions both conduction mechanisms can be operative. The combined effect of the two mechanisms is established by determining the resultant resistivity using the equation for parallel resistances. In the following section the mechanics of combining the effects of the principal factors controlling the resistivity of fly ash will be given. The result is a prediction of resistivity as a function of temperature for a given coal and coal ash composition.

SECTION 7

RESISTIVITY PREDICTION METHOD

The resistivity of a collected layer of fly ash is affected by certain physical, chemical, and electrical factors. It is known that the ash layer porosity and the available conducting surface resulting from the microplacement of a given particle size distribution have a significant effect on resistivity. However, since there is presently no way of anticipating these factors from core bore samples, an attempt was made to circumvent this problem by incorporating into the study a large number of fly ash specimens having a wide range of properties. Hopefully, this technique has minimized the influence of the physical characteristics of specific ashes. The chemical factors include the chemical composition of the fly ash and the concentrations of water vapor and sulfur trioxide in the flue gas. The influence of these factors has been quantitatively defined in a preceding section. The effect of electrical stress on resistivity was also discussed previously.

The predictive method attempts to accomodate the most general case; that is, the prediction of fly ash resistivity from a core bore sample of a coal that has never been commercially fired. The various steps used in the prediction of resistivity are discussed below so that one can calculate resistivity as a function of temperature from the expressions and graphs previously given or one can use the computer program that is given in the next section for this purpose.

REQUIRED INPUT DATA

The required input data are obtained from the as-received, ultimate coal analysis and the chemical analysis of the coal ash. Since the predicted resistivity is sensitive to the chemical factors involved, it is emphasized that one should use the best available coal and ash specimens and that accurate quantitative analyses are available.

For this research program, the ASTM D3176 procedure was used to determine the ultimate coal analysis. From this information, a stoichiometric combustion calculation to determine the flue gas composition based on 30% excess air is made. The 30%

excess air value was selected by evaluating the precipitator inlet flue gas analyses submitted by the forty utility operators that assisted in this program by supplying ash samples and useful data. The combustion calculation will not be reproduced here, because it is a familiar step to the concerned industry. The output of the computer program that follows shows the general form of the calculation. Two factors from the computed flue gas analysis are used in the resistivity prediction. These are the water concentration in volume percent and the sulfur dioxide concentration as the dry, volume fraction in parts per million. For the example calculation that follows, the water concentration equals 9.9% and the sulfur dioxide concentration equals 1350 ppm.

The coal ash was produced by first ashing according to the ASTM D3174 procedure and then reigniting a specimen at 1050°C ± 10°C in still air for 10 to 12 hours (overnight). This ignition schedule was found to be optimum for the several coals used in this study. The good agreement between the fly ash and coal ash chemical compositions will be shown later in this report in the section describing the testing of the predictive technique. When other research[19] is examined, the ignition temperature established in this work by trial and error seems reasonable. It is hoped that in the future an objective technique will be established to determine the optimum ignition temperature for each specific coal sample prior to chemical analysis.

The coal ash is chemically analyzed, and the data are reported as oxides in weight percent. After normalizing the weight percentages to sum 100%, each oxide percentage is divided by the respective molecular weight to obtain the mole fraction. Each mole fraction is divided by the sum of the mole fractions and multiplied by 100 to get the molecular percentage as oxides. Each molecular percentage is multiplied by the decimal fraction of cations in the given oxide to obtain the atomic concentration. An example of the calculation is shown in Table IV. The following atomic concentrations taken from Table IV are of interest for the resistivity prediction: (a) the sum of lithium and sodium, 0.36, (b) the sum of magnesium and calcium, 10.7, (c) iron, 1.3, and (d) potassium, 0.65.

CALCULATION OF RESISTIVITY

Using the aforementioned input data, resistivity can be calculated as a function of the usual temperature spectrum experienced by both cold-side and hot-side precipitators. The entire resistivity-reciprocal absolute temperature curve is produced from the combination of three separately calculated curves. These three resistivity-temperature relationships reflect the influence of: (a) ash composition, ρ_v, (b) ash composition-water concentration, ρ_s, and (c) concentration of sulfuric acid vapor, ρ_a.

Table IV.

Illustrative Example of the Calculation of the Atomic Concentration of Cations in Coal Ash.

Oxide	Determined Wt %	Normalized Wt %	Molecular Weight	Mole Fraction	Molecular Percentage	Cationic Fraction	Atomic Concentration of Cation
Li_2O	0.01	0.01	29.88	0.00033	0.022	0.67	0.015
Na_2O	0.46	0.47	61.98	0.00758	0.517	0.67	0.346
K_2O	1.30	1.34	94.20	0.01423	0.970	0.67	0.650
MgO	2.82	2.91	40.31	0.07219	4.921	0.50	2.461
CaO	13.10	13.52	56.08	0.24108	16.433	0.50	8.217
Fe_2O_3	7.46	7.70	159.70	0.04822	3.287	0.40	1.315
Al_2O_3	18.40	19.00	101.96	0.18635	12.703	0.40	5.081
SiO_2	49.60	51.22	60.09	0.85239	58.103	0.33	19.174
TiO_2	0.64	0.66	79.90	0.00826	0.563	0.33	0.186
P_2O_5	0.57	0.59	141.94	0.00416	0.284	0.29	0.082
SO_3	2.50	2.58	80.06	0.03223	2.197	0.25	0.549
Sum	96.86	100.00	---	1.46702	100.000		38.076

Calculation of Volume Resistivity, ρ_V

This value at a reciprocal absolute temperature of 1000/T(°K) = 1.6 can be obtained graphically from Figure 11 or can be computed from:

$$\log \rho_{V,\,1.6} = 8.9434 - [1.8916 \log x] - [0.9696 \log y] + [1.2370 (\log z - \log 2.5)], \qquad (7)$$

where x, y, and z are the atomic concentrations of Li + Na, Fe, and Mg + Ca, respectively.

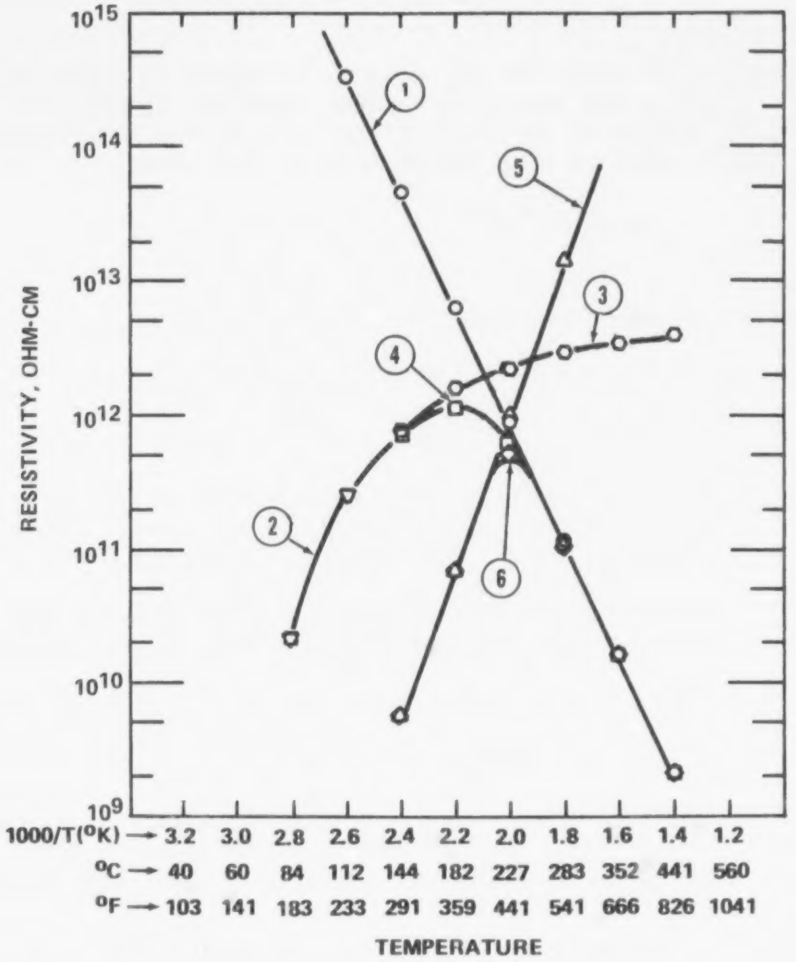
Expression (7) was derived by summing the three curves shown in Figure 11 and converting to base 10 logarithms. Substituting the concentrations from Table IV for x, y, and z into Equation (7), the value of log $\rho_{V,\,1.6}$ becomes 10.4533. Using Equation (3), this value for log $\rho_{V,\,1.6}$ which is based on the experimental voltage gradient of 2 kV/cm can be adjusted to the arbitrarily selected gradient of 10 kV/cm used in this predictive technique. Then the value of log ρ_V at 1000/T(°K) = 1.6 and E = 10 kV/cm equals 10.2133, and $\rho_V = 1.6 \times 10^{10}$ ohm cm.

By inserting this corrected value of log $\rho_{V,1.6}$ in Equation (1) and letting θ equal 0.86 electron volts, the average value for this study, the preexponential term of Equation (1) is calculated. Knowing this term, values of ρ_V at all temperatures of interest can be calculated. In this manner log ρ_V at 1000/T(°K) = 1.4 was calculated as 9.3464 ($\rho_{V,\,1.4} = 2.2 \times 10^9$ ohm cm), and curve number one in Figure 24 was constructed.

Calculation of Surface Resistivity, ρ_S

The values of log ρ_S at reciprocal absolute temperatures of 1000/T(°K) = 2.8 and 2.6 for E = 2 kV/cm and a 9.0% water concentration can be graphically interpreted or calculated using the expressions shown in Figures 2 and 3, respectively. These values then can be adjusted to an E value of 10 kV/cm and to the example environmental water concentration of 9.9% using Equations (3) and (2), respectively. After these corrections are applied, the values of log ρ_S are 10.3255 and 11.4095 for reciprocal absolute temperature of 1000/T(°K) = 2.8 and 2.6, respectively and $\rho_{S,\,2.8}$ and $\rho_{S,\,2.6}$ are 2.1×10^{10} ohm cm and 2.6×10^{11} ohm cm, respectively.

If this technique for calculating ρ_S is used at higher temperatures and the values of ρ_S are combined with the previously calculated ρ_V values using the parallel resistance expression,



CURVE NUMBER	RESISTIVITY DESIGNATION	EQUATION NUMBER	SYMBOL
1	ρ_v	1	○
2	ρ_s	FIGURES 2 & 3	▽
3	ρ_s	8	⬡
4	ρ_{vs}	12	□
5	ρ_a	14	△
6	ρ_{vsa}	15	◇

Figure 24. Predicted resistivity as a function of temperature.

a discontinuity can develop in the resultant resistivity versus reciprocal absolute temperature curve. This can occur because of the significant effect of the alkaline earth elements on the high temperature resistivity, ρ_v. If one were interested in calculating the predicted resistivity at a single cold-side precipitator temperature, for example 1000/T(°K) = 2.4 (291°F), the above procedure used to calculate the values at 1000/T(°K) 2.8 and 2.6 would be adequate.[20]

However, to extend the ρ_s versus reciprocal absolute temperature curve to some limiting value such as 1000/T(°K) = 1.4 from the value computed at 1000/T(°K) = 2.6, an expression[21,13,22] previously rationalized and found useful was used:

$$\rho_s = \rho_{so} e^{-W K_0 e^{K_1/T}} \tag{8}$$

Expressed in logarithmic form this equation is:

$$\log \rho_s = \log \rho_{so} - [\log e\, K_0 \exp (K_1/T)]\, W \tag{9}$$

where

ρ_s = surface resistivity influenced principally by temperature, ash composition, water vapor concentration and specific surface,

ρ_{so} = maximum surface resistivity as the effect of water vapor approaches zero at high temperatures,

W = water vapor concentration in volume percent,

T = absolute temperature, °K,

K_0 and K_1 = parameters related to the physical and chemical properties of the water vapor having the dimensions 1/volume percent water and degrees Kelvin, respectively.

The quantity shown in brackets in Equation (9) defines the change in the logarithm of resistivity as a function of water concentration at a given temperature. This value was previously defined as $\bar{S}_w$ in Equation (2); that is,

$$\bar{S}_w = \log e\, K_0 \exp (K_1/T) \text{ and} \tag{10}$$

$$\log \bar{S}_w = \log (K_0 \log e) + K_1 \log e\, (1/T). \tag{11}$$

Figure 14 graphically illustrated Equation (11). Using the numerical values for the intercept and slope calculated from the regression analysis of the data shown in Figure 14, the values for K_0 and K_1 were determined, respectively, as 7.3895×10^{-4} and 2.3033×10^3.

Knowing K_0, K_1, the water concentration, and $\rho_{S,\,2.6}$, the value of ρ_{SO} was calculated from Equation (8). After determining ρ_{SO}, the values of ρ_S at 1000/T(°K) = 2.4, 2.2, 2.0, 1.8, 1.6, and 1.4 were computed. The curve showing these values for surface resistivity, ρ_S, as a function of temperature are shown in Figure 24, curve numbered 3.

Calculation of Combined Volume and Surface Resistivities, ρ_{VS}

Although in the absence of significant sulfuric acid vapor the surface and volume conduction mechanisms are both dependent on alkali metal ions for charge carriers, the two processes afford separate conduction paths through the ash layer. Resistivity as a function of temperature for the combined effect of surface (ρ_S) and volume (ρ_V) resistivities can be calculated using the expression for the sum of parallel resistances stated in terms of resistivity:

$$\rho_{VS} = \frac{\rho_V \, \rho_S}{\rho_V + \rho_S} \tag{12}$$

It becomes apparent that when $\rho_V \gg \rho_S$ then $\rho_{VS} \sim \rho_S$ and when $\rho_S \gg \rho_V$ then $\rho_{VS} \sim \rho_V$. Curve number 4 in Figure 24 shows the resultant ρ_{VS}.

Calculation of Acid Resistivity, ρ_a

In previous discussion it was concluded that surface conduction resulting from the adsorption of sulfuric acid vapor occurs by a mechanism unrelated to that occurring due to the interaction of the ash surface and water vapor. Consequently the surface resistivity resulting from the adsorption of sulfuric acid vapor, ρ_a, is calculated separately in a manner analogous to those used to calculate ρ_S and ρ_V. Finally, the effect of adsorbed acid on the complete resistivity-temperature relationship is incorporated by combining ρ_a with ρ_{VS} using the expression for parallel resistances.

Present knowledge suggests that the effect of adsorbed acid on resistivity is a function of fly ash composition in that certain compositions have greater affinity for the acid. Because of this, two separate calculations are used to define ρ_a as a function of environmental sulfur trioxide concentration and temperature.

If the combined atomic concentration of magnesium and calcium $\leq$ 3.5% or the potassium concentration is $\geq$ 1.0%, then:

$$\begin{aligned} \log \rho_a = {} & [12.9676 - (0.3075\, C_{SO_3})] + \\ & [10.1048\,(2.37 - 1000/T)]. \end{aligned} \tag{13}$$

If the combined atomic concentration of magnesium and calcium is > 3.5% and the potassium atomic concentration is < 1.0%, then:

$$\log \rho_a = [12.1612 - (0.3712\, C_{so^3})] + [5.6673\,(2.37 - 1000/T)]. \quad (14)$$

where

C_{so^3} = concentration of sulfur trioxide in dry volume ppm and

T = absolute temperature in °K.

The chemical limitations applied to Equations (13) and (14) generally define what is commonly referred to as eastern and western ash, respectively. Equations (13) and (14) were obtained by respectively substituting Equations (4) and (5) into Equation (6) utilizing the appropriate slope value. In either case above, the calculated value of ρ_a is that concomitant with an E value of 2 kV/cm. As in the case of the calculations of ρ_v and ρ_s, the ρ_a values at 2 kV/cm are adjusted to 10 kV/cm using Equation (3).

In the example problem being considered, the stoichiometrically calculated concentration of sulfur dioxide was 1350 ppm, dry volume. The concentration of sulfur trioxide used in the prediction of resistivity, C_{SO_3}, is taken as 0.4% of the computed C_{SO_2} value. In this case, C_{SO_3} equals 5.4 ppm. This method of computing the C_{SO_3} concentration is based on the review of information from seventeen field tests in which both sulfur dioxide and sulfur trioxide determinations were made using specimens taken at the inlet to the precipitator. It is assumed that the degree of equilibrium between the fly ash and sulfuric acid vapor at the inlet to a precipitator is similar to that existing at the surface of an ash layer after long-time exposure to a laboratory test environment.

In the example problem, the ash analysis indicates that Equation (14) should be used to compute ρ_a with C_{SO_3} equal to 5.4 ppm. After correcting to E = 10 kV/cm using Equation (3), values of ρ_a for several values of 1000/T(°K) were plotted in Figure 24, curve number 5. No data are computed for values of 1000/T(°K) > 2.4. There are two reasons for this. One, no significant experimental data were acquired at temperatures lower than this point. Two, at the lower temperatures, the acid dew point is approached. It is not possible to precisely determine this value, and the effect of condensed acid on resistivity has not been measured.

Calculation of Combined Volume, Surface, and Acid Resistivities, ρ_{vsa}

The curve for resistivity as a function of temperature is completed to include the effect of adsorbed sulfuric acid vapor by combining the values for ρ_a and ρ_{vs} using the equation for parallel resistances expressed in terms of resistivity:

$$\rho_{vsa} = \frac{\rho_a \, \rho_{vs}}{\rho_a + \rho_{vs}} \quad (15)$$

When $\rho_a >> \rho_{vs}$, $\rho_{vsa} \sim \rho_{vs}$ and when $\rho_{vs} >> \rho_a$, $\rho_{vsa} \sim \rho_a$. Curve number 6 resulting from the use of Equation (15) is indicated in Figure 24. Comparison of the resistivity-temperature relationships ρ_{vs} and ρ_{vsa} shows the effectiveness of sulfuric acid vapor as an agent for attenuating resistivity. The example used to illustrate the method of predicting resistivity in this section is also used to illustrate the computer program described next.

SECTION 8

COMPUTER PROGRAM FOR PREDICTING RESISTIVITY

In the preceding section a method was described with which resistivity as a function of temperature can be calculated. Using an assumed as-received, ultimate coal analysis and the concomitant coal ash analysis as input information, the method was illustrated in detailed steps by computing the resistivity from the many equations and correlations established earlier in the report. In this section a computer program is given to determine resistivity as a function of temperature using the same illustrative example. The program written in FORTRAN is shown in documented form as Table V. The program written in disk BASIC for a TRS-80 microcomputer is shown as Table VI.

The input for the FORTRAN program is shown on a multiple-card layout form, Figure 25, indicating that a data set of three punched cards are required. The first card contains two variables: IEND, an end of data indicator, and ITITLE, the title or designation information. For each data set of three cards, IEND should be blank. A card with IEND equal 9 should follow the last card of the last data set to stop the program. The second card contains the input data for the variables XIN, SO2, W and E. The third card contains the input data for the variable XMWPO. Figure 26 illustrates the three cards punched for the example coal and coal ash.

Input for the BASIC program is from the computer keyboard. The program prompts the user and provides opportunity for error corrections. The program also allows the user to change sulfur trioxide after initial resistivity is predicted. The BASIC program is essentially a direct translation of the FORTRAN code.

The program can be used in several ways. The principal mode is to determine ash resistivity at a field strength of 10 kV/cm from a core bore sample of coal in which case the data for variables XIN and XMWPO are supplied respectively from coal and coal ash analyses determined in the manner described in the previous section. In this mode the variables SO2, W and E are left blank.

A fly ash chemical composition can be used for the variable XMWPO instead of a coal ash analysis. In this case, the loss on ignition value normally reported for a fly ash analysis is

```
C                                  TABLE V
C
C     COMPUTER PROGRAM FOR PREDICTING RESISTIVITY
C
C**********************************************************************
C*                                                                    *
C*    THIS PROGRAM IS DESIGNED TO COMPUTE FLY ASH RESISTIVITY AS A    *
C*    FUNCTION OF TEMPERATURE FROM COAL AND COAL ASH ANALYSES.        *
C*    DR. R. E. BICKELHAUPT OF SOUTHERN RESEARCH INSTITUTE WAS THE    *
C*    PRINCIPAL INVESTIGATOR.  THE RESEARCH WAS SPONSORED BY THE      *
C*    PARTICULATE TECHNOLOGY BRANCH, INDUSTRIAL ENVIRONMENTAL         *
C*    RESEARCH LABORATORY OF THE ENVIRONMENTAL PROTECTION AGENCY.     *
C*    DR. L. E. SPARKS, PROJECT OFFICER.                              *
C*                                                                    *
C**********************************************************************
C
      DIMENSION XIN(7),WTM(6),XO2(5),XDA(5),O2(7),DA(7),WET(5),DRY(5),
     *   XMOLES(7),ITITLE(75),XMWPO(11),WPOLC(11),XMWO(11),XMF(11),
     *   XMPO(11),XMPE(11),TEMP(8),TK(8),KT(8),RVSA(8),PFO(11),ICT(8),
     *   RV(8),RS(8),RVS(8),RA(8),IFT(8),S1(2),YCEPT(2),SW(2)
C
      EQUIVALENCE (RS(7),RS26)
C
C**********************************************************************
C*                                                                    *
C*  DEFINITION OF VARIABLES IN DATA STATEMENT                         *
C*                                                                    *
C*  TEMP   RECIPROCAL ABSOLUTE TEMPERATURE = 1000/T DEGREES K         *
C*  TK     TEMPERATURE DEGREES KELVIN                                 *
C*  ICT    TEMPERATURE DEGREES CENTIGRADE - INTEGER FORMAT FOR PRINTING*
C*  IFT    TEMPERATURE DEGREES FARENHEIT - INTEGER FORMAT FOR PRINTING *
C*  KT     TEMPERATURE DEGREES KELVIN - INTEGER FORMAT FOR PRINTING   *
C*  XO2    MOLES OF OXYGEN REQUIRED PER MOLE OF C,H2,O2,N2,S          *
C*         FOR COMBUSTION                                             *
C*  XDA    MOLES OF DRY AIR REQUIRED PER MOLE OF C,H2,O2,N2,S         *
C*         FOR COMBUSTION                                             *
C*  S1     SLOPE OF LN RHO VS ATOMIC % LITHIUM + SODIUM AT            *
C*         1000/T DEGREES K = 2.6 AND 2.8 RESPECTIVELY                *
C*  YCEPT  INTERCEPT OF LN RHO VS ATOMIC % LITHIUM + SODIUM AT        *
C*         1000/T DEGREES K = 2.6 AND 2.8 RESPECTIVELY                *
C*  SW     SLOPE OF LOG RHO VS VOLUME % WATER AT                      *
C*         1000/T DEGREES K = 2.6 AND 2.8 RESPECTIVELY                *
C*  WTM    MOLECULAR WEIGHTS FOR C,H2,O2,N2,S,H2O                     *
C*  PFO    % CATIONS FOR REPORTED ASH OXIDES                          *
C*  XMWO   MOLECULAR WEIGHTS OF REPORTED OXIDES                       *
C*                                                                    *
C**********************************************************************
C
      DATA TEMP/1.4,1.6,1.8,2.0,2.2,2.4,2.6,2.8/
      DATA TK/714.0,625.0,556.0,500.0,455.0,417.0,385.0,357.0/
      DATA ICT/441,352,283,227,182,144,112,84/
      DATA IFT/826,666,541,441,359,291,233,183/
      DATA KT/714,625,556,500,455,417,385,357/
      DATA XO2/1.00,0.50,-1.00,0.00,1.00/
      DATA XDA/4.76,2.38,-4.76,0.00,4.76/
      DATA S1/-2.233348,-2.061840/
      DATA YCEPT/24.807004,22.641601/
      DATA SW/0.1280,0.2029/
      DATA WTM/12.01,2.02,32.00,28.01,32.06,18.02/
      DATA PFO/3*66.66,2*50.00,2*40.00,2*33.33,28.57,25.00/
      DATA XMWO/29.88,61.98,94.20,40.31,56.08,159.70,101.96,60.09,
     *   79.90,141.94,80.06/
C
C*    STATEMENT FUNCTION ROUNDS TO THE NEAREST 0.001                   *
      ROUND(X) = AINT(X*1000.0+SIGN(0.5,X))/1000.0
C
C***********************************************************************
C*                                                                     *
C*  CONSTANTS                                                          *
C*                                                                     *
C*  CX   30% EXCESS AIR FUNCTION                                       *
C*  XC   LOG 2.5                                                       *
C*  SV   SLOPE LOG RHO IN ARRHENIUS EQUATION VS RECIPROCAL             *
C*       ABSOLUTE TEMPERATURE                                          *
C*  XK0  CONSTANT                                                      *
C*  XK1  CONSTANT                                                      *
C*  T    TEMPERATURE = 385.0 DEGREES K                                 *
C*  SF   SLOPE LOG RHO VS FIELD STRENGTH                               *
C*                                                                     *
C***********************************************************************
C
      CX = 130.0/100.0
      XC = ALOG10(2.5)
      SV = 4.3345*10.0**3
      XK0 = 7.3894*10.0**(-4)
      XK1 = 2.3033*10.0**3
      T = 385.0
      SF = 0.03
C
C*    READ FROM CARD IEND AND DATA IDENTIFICATION                      *
    5 READ (2,6) IEND,ITITLE
    6 FORMAT (I1,75A1)
C
C*    IEND = 9  STOPS THE PROGRAM                                      *
      IF (IEND .EQ. 9) GO TO 999
C
C*    ISKIP IS VARIABLE FOR PRINT SPACING                              *
      ISKIP = 0
C
C*    READ DATA CARD                                                   *
C*    XIN = AS RECEIVED ULTIMATE COAL ANALYSIS                         *
C*    SO2 = PPM SO2                                                    *
C*    W = VOLUME % WATER                                               *
C*    E = FIELD STRENGTH                                               *
C*    SO2, W, AND E ARE OPTIONAL AS INPUT VARIABLES                    *
C*    THE PROGRAM WILL CALCULATE IF NOT INPUT                          *
      READ (2,1) XIN,SO2,W,E
    1 FORMAT (12F6.0)
C
C*    READ DATA CARD - XMWPO IS ASH ANALYSIS                           *
      READ (2,1) XMWPO
C
C*    THE DEFAULT VALUE FOR FIELD STRENGTH E IS 10.0                   *
   15 IF (E .EQ. 0.0) E=10.0
C
C*    PRINT IDENTIFICATION                                             *
      WRITE (3,7) ITITLE
    7 FORMAT ('1', 5X,'RESISTIVITY PREDICTION BASED ON WORK DONE BY'/
     *    6X,'DR. ROY BICKELHAUPT OF SOUTHERN RESEARCH INSTITUTE.'/
     *    6X,'THE RESEARCH WAS SPONSORED BY THE PARTICULATE'/
     *     6X,'TECHNOLOGY BRANCH, INDUSTRIAL ENVIRONMENTAL RESEARCH'/
     *     6X,'LABORATORY OF THE ENVIRONMENTAL PROTECTION AGENCY,'/
     *     6X,'DR. L. E. SPARKS, PROJECT OFFICER.' /// 1X,75A1//)
C
C*    IF W AND SO2 ARE GIVEN AS INPUT DONT CALCULATE - SKIP TO 75        *
      IF ((W.NE.0.) .AND. (SO2.NE.0.)) GO TO 75
C
      ISKIP = 1
C
C*    SUM COAL ANALYSIS                                                   *
      SUMIN = 0.0
      DO 10  I=1,7
      SUMIN = SUMIN + XIN(I)
   10 CONTINUE
      IF (SUMIN .EQ. 100.0) GO TO 30
C
C*    NORMALIZE COAL ANALYSIS                                             *
      DO 20  I=1,7
      XIN(I) = XIN(I)/SUMIN*100.0
   20 CONTINUE
      SUMIN = 100.0
C
C*    CALCULATE AND SUM MOLES - MOLES = %/MOLECULAR WEIGHT                *
   30 SUMOLE = 0.0
      DO 40  I=1,6
      XMOLES(I) = ROUND(XIN(I)/WTM(I))
      SUMOLE = SUMOLE + XMOLES(I)
   40 CONTINUE
C
C*    CALCULATE AND SUM MOLES O2 AND DRY AIR                              *
C*    REQUIRED FOR COMBUSTION AT 100% TOTAL AIR                           *
      SUMO2 = 0.0
      SUMDA = 0.0
      DO 50  I=1,5
      IF (I .EQ. 4) GO TO 50
      O2(I) = ROUND(XMOLES(I) * XO2(I))
      DA(I) = ROUND(XMOLES(I) * XDA(I))
      SUMO2 = SUMO2 + O2(I)
      SUMDA = SUMDA + DA(I)
   50 CONTINUE
C
C*    PRINT                                                               *
      WRITE (3,2) (XIN(I),XMOLES(I),O2(I),DA(I),I=1,7),SUMIN,SUMOLE,
     *   SUMO2,SUMDA
    2 FORMAT (T41,'REQUIRED FOR COMBUSTION'/ T43,'MOLES/100 LB FUEL'/
     *   T8,'AS RECEIVED',T26,'MOLES PER',T43,'AT 100% TOTAL AIR'/
     *   T7,'ULTIMATE COAL',T28,'100 LB',T41,23('=')/ T10,'ANALYSIS',
     *   T29,'FUEL',T45,'O2',T55,'DRY AIR'/ T7,13('='),T26,9('='),T43,
     *   6('='),T55,7('=')/ ' C',T11,F6.2,T27,F6.3,T43,F6.3,T56,F6.3/
     *   ' H2',     T11,F6.2,T27,F6.3,T43,F6.3,T56,F6.3/
     *   ' O2',     T11,F6.2,T27,F6.3,T43,F6.3,T56,F6.3/
     *   ' N2',     T11,F6.2,T27,F6.3,T43,F6.3,T56,F6.3/
     *   ' S ',     T11,F6.2,T27,F6.3,T43,F6.3,T56,F6.3/
     *   ' H2O',    T11,F6.2,T27,F6.3,T43,F6.3,T56,F6.3/
     *   ' ASH',    T11,F6.2,T27,F6.3,T43,F6.3,T56,F6.3//
     *   ' SUM',    T11,F6.2,T27,F6.3,T43,F6.3,T56,F6.3//)
C
C*    CALCULATE MOLES O2 AND DRY AIR REQUIRED FOR COMBUSTION              *
C*    AT 30% EXCESS AIR                                                   *
      XSUMO2 = ROUND(CX * SUMO2)
      XSUMDA = ROUND(CX * SUMDA)
C
C*    CALCULATE EXCESS AIR AND EXCESS O2                                 *
      EXAIR = XSUMDA - SUMDA
      EXO2 = XSUMO2 - SUMO2
C
C*    PRINT                                                              *
      WRITE (3,3) XSUMO2,XSUMDA,EXAIR,EXO2
    3 FORMAT (T34,'REQ FOR COMBUSTION'/ T35,'MOLES/100 LB FUEL'/
     *   T36,'@30% EXCESS AIR'/ T34,18('=')/ T37,'O2',T44,'DRY AIR'/
     *   T35,6('='),3X,7('=')/ ' O2 AND AIR * 130/100 TOTAL',7X,F6.3,
     *   4X,F6.3/ ' EXCESS AIR',T45,F6.3/ ' EXCESS O2',T35,F6.3//)
C
C*    CALCULATE PRODUCTS OF COMBUSTION                                   *
      XMOLES(2) = XMOLES(2) + XMOLES(6) + (XSUMDA*29.0*0.013)/18.0
      XMOLES(3) = XMOLES(5)
      XMOLES(4) = XMOLES(4) + (XSUMDA*0.79)
      XMOLES(5) = EXO2
C
C*    CALCULATE % BY VOLUME - WET BASIS                                  *
      SUMWET = 0.0
      DO 60  I=1,5
      SUMWET = SUMWET + XMOLES(I)
   60 CONTINUE
C
C*    CALCULATE % BY VOLUME - DRY BASIS                                  *
      SUMDRY = SUMWET - XMOLES(2)
C
C*    SUM WET AND DRY                                                    *
      DO 70  I=1,5
      WET(I) = ROUND(XMOLES(I)/SUMWET*100.)
      DRY(I) = ROUND(XMOLES(I)/SUMDRY*100.0)
   70 CONTINUE
      DRY(2) = 0.0
C
C*    PRINT                                                              *
      WRITE (3,4) (XMOLES(I),WET(I),DRY(I),I=1,5),SUMWET,SUMDRY
    4 FORMAT (T17,' PRODUCTS OF COMBUSTION'/ T11,37('=')/ T13,'TOTAL'/
     *   T11,'MOLES/100',6X,'% BY VOL',6X,'% BY VOL'/ T12,'LB FUEL',
     *   6X,'WET BASIS',5X,'DRY BASIS'/ T11,9('='),5X,9('='),5X,9('=')/
     *   ' CO2',8X,F6.3,8X,F6.3,8X,F6.3/ ' H2O',8X,F6.3,8X,F6.3,8X,F6.3/
     *   ' SO2',8X,F6.3,8X,F6.3,8X,F6.3/ ' N2',9X,F6.3,8X,F6.3,8X,F6.3/
     *   ' O2',9X,F6.3,8X,F6.3,8X,F6.3/ ' SUM WET',4X,F6.3/ ' SUM DRY',
     *   4X,F6.3//)
C
C*    IF W AND SO2 ARE NOT GIVEN AS INPUT (=0.0) SET W AND               *
C*    SO2 FROM PREVIOUS CALCULATIONS                                     *
   75 IF (W .EQ. 0.) W=WET(2)
      IF (SO2 .EQ. 0.) SO2=DRY(3)*10000.0
C
C*    SO2 = -1.0 ON DATA CARD INDICATES SO2 SHOULD BE 0.0                *
      IF (SO2 .EQ. -1.0) SO2=0.
C
C*    CALCULATE SO3 FROM SO2                                             *
      SO3 = 0.004*SO2
C
C*    REPRESENT SO2 AND E AS INTEGERS                                    *
      ISO2 = SO2
      IE = E
C
```

```
C*    ROUND W AND SO3 TO THE NEAREST 0.1                                 *
      W = AINT(W*10.0+SIGN(0.5,W))/10.0
      SO3 = AINT(SO3*10.0+SIGN(0.5,SO3))/10.0
C
C*    PRINT                                                              *
      WRITE (3,11) W,ISO2,SO3,IE
   11 FORMAT (' H2O',F14.1/ ' SO2',8X,I6/ ' SO3',F14.1// ' E',10X,I6)
C
C*    SUM ASH ANALYSIS                                                   *
      SUMX = 0.0
      DO 80  I=1,11
      SUMX = SUMX + XMWPO(I)
   80 CONTINUE
C
C*    NORMALIZE AND SUM ASH ANALYSIS                                     *
      SUMA = 0.0
      DO 90  I=1,11
      WPOLC(I) = (XMWPO(I)/SUMX)*100.0
      SUMA = SUMA + WPOLC(I)
   90 CONTINUE
C
C*    CALCULATE AND SUM MOLE FRACTION - XMF                              *
      SUM = 0.0
      DO 100  I=1,11
      XMF(I) = WPOLC(I)/XMWO(I)
      SUM = SUM + XMF(I)
  100 CONTINUE
C
C*    CALCULATE MOLECULAR % AS OXIDES - XMPO                             *
C*    CALCULATE AND SUM ATOMIC CONCENTRATIONS OF CATIONS - XMPE          *
      SUMB = 0.0
      DO 110  I=1,11
      XMPO(I) = XMF(I)/SUM
      XMPE(I) = XMPO(I) * PEO(I)
      SUMB = SUMB + XMPE(I)
  110 CONTINUE
C
C*    SL = ATOMIC CONCENTRATION LITHIUM + SODIUM                         *
C*    CM = ATOMIC CONCENTRATION CALCIUM + MAGNESIUM                      *
C*    XIRON = ATOMIC CONCENTRATION IRON                                  *
C*    POT = ATOMIC CONCENTRATION POTASSIUM                               *
      SL = XMPE(1) + XMPE(2)
      CM = XMPE(4) + XMPE(5)
      XIRON = XMPE(6)
      POT = XMPE(3)
C
C*    ROUND SL AND POT TO THE NEAREST 0.01                               *
C*    ROUND CM AND XIRON TO THE NEAREST 0.1                              *
      SL = AINT(SL*100.+SIGN(0.5,SL))/100.
      CM = AINT(CM*10.+SIGN(0.5,CM))/10.
      XIRON = AINT(XIRON*10.+SIGN(0.5,XIRON))/10.
      POT = AINT(POT*100.+SIGN(0.5,POT))/100.
C
C*    CLASSIFY ASH BASED OF AFFINITY FOR ACID                            *
C*    L = 2  CALCIUM + MAGNESIUM > 3.5 AND POTASSIUM < 1.0               *
C*    L = 1  OTHERWISE                                                   *
      L = 1
      IF ((CM.GT.3.5) .AND. (POT.LT.1.0)) L=2
C
      IF (ISKIP .EQ. 1) WRITE(3,14)
   14 FORMAT ('1')
C
C*      PRINT                                                            *
        WRITE (3,12) (XMWPO(I),WPOLC(I),XMPE(I),I=1,11),SUMX,SUMA,SUMB
   12 FORMAT (T23,'CORRECTED'/ T14,'ASH',T26,'ASH',T40,'ATOMIC'/
     *   T11,'ANALYSIS',T24,'ANALYSIS',T36,'CONCENTRATION'/
     *   T11,8('='),T23,9('='),T36,13('=')/ ' LI2O',F12.2,F13.2,F15.3/
     *   ' NA2O',F12.2,F13.2,F15.3/ ' K2O',2F13.2,F15.3/ ' MGO',2F13.2,
     *   F15.3/ ' CAO',2F13.2,F15.3/ ' FE2O3',F11.2,F13.2,F15.3/
     *   ' AL2O3',F11.2,F13.2,F15.3/ ' SIO2',F12.2,F13.2,F15.3/ ' TIO2',
     *   F12.2,F13.2,F15.3/ ' P2O5',F12.2,F13.2,F15.3/ ' SO3',2F13.2,
     *   F15.3// ' SUM',2F13.2,F15.3//)
C
  115 WRITE (3,8) SL
    8 FORMAT (' SUM OF LITHIUM AND SODIUM ATOMIC CONCENTRATIONS',
     *   5X,F6.2)
      WRITE (3,16) CM,XIRON,POT
   16 FORMAT (' SUM OF MAGNESIUM AND CALCIUM ATOMIC CONCENTRATIONS',
     *   2X,F6.1/ ' IRON ATOMIC CONCENTRATION',27X,F6.1/
     *   ' POTASSIUM ATOMIC CONCENTRATION',22X,F6.2//)
C
C*      RV16 IS THE RESISTIVITY AT 1000/T DEGREES K = 1.6 BASED ON       *
C*      EXPERIMENTAL CORRELATION OF RESISTIVITY AS A FUNCTION OF         *
C*      ASH COMPOSITION                                                  *
        RV16 = 8.9434 -1.8916*ALOG10(SL) -0.9696*ALOG10(XIRON)
     *     +1.2370*(ALOG10(CM)-XC)
C
C*      RV0 IS THE PRE-EXPONENTIAL TERM IN THE ARRHENIUS EQUATION        *
        RV0 = RV16 - SV/625.0
C
C*      RV IS ANY RESISTIVITY DEFINED BY THE ARRHENIUS EQUATION          *
C*      ADJUST EACH RV FOR THE EFFECT OF E                               *
        DO 116  I=1,8
        RV(I) = RV0 + SV/TK(I)
        RV(I) = RV(I) - (E-2.0)*SE
        RV(I) = 10.0**RV(I)
  116 CONTINUE
C
C*      RSC IS SURFACE RESISTIVITY AS A FUNCTION OF                      *
C*      COMPOSITION AT 2.6 AND 2.8                                       *
C*      RSCW IS LOG SURFACE RESISTIVITY AS A FUNCTION OF                 *
C*      COMPOSITION AND VOLUME % WATER AT 2.6 AND 2.8                    *
C*      RSCWF IS LOG SURFACE RESISTIVITY AS A FUNCTION OF COMPOSITION,   *
C*      VOLUME % WATER, AND FIELD STRENGTH AT 2.6 AND 2.8                *
C*      RS IS SURFACE RESISTIVITY (HERE ONLY CALCULATED FOR 2.6 AND 2.8) *
        DO 117  I=1,2
        J = I + 6
        RSC = EXP(S1(I)*ALOG(SL)+YCEPT(I))
        RSCW = ALOG10(RSC) - (W-9.0)*SW(I)
        RSCWF = RSCW - (F-2.0)*SF
        RS(J) = 10.0**RSCWF
  117 CONTINUE
C
C*      RS0 IS THE PRE-EXPONENTIAL TERM IN THE DOUBLE                    *
C*      EXPONENTIAL SURFACE RESISTIVITY EQUATION                         *
        RS0 = RS26/EXP(-W*XK0*EXP(XK1/T))
C
C*      RS IS SURFACE RESISTIVITY (CALCULATED FOR 1.4 - 2.4)             *
        DO 119  I=1,6
        RS(I) = RS0 * EXP(-W*XK0*EXP(XK1/TK(I)))
  119 CONTINUE
C
C*    RVS IS THE RESISTIVITY RESULTING FROM THE COMBINATION OF           *
C*    VOLUME AND SURFACE RESISTIVITIES USING THE EXPRESSION              *
C*    FOR PARALLEL RESISTANCES                                           *
      DO 120  I=1,8
      RVS(I) = RV(I)*RS(I)/(RV(I)+RS(I))
  120 CONTINUE
C
C*    IF SO2, SO3 = 0, DO NOT ADJUST RESISTIVITY                         *
C*    FOR EFFECT OF ACID                                                 *
      IF (SO2 .NE. 0.) GO TO 1202
      DO 1201  I=1,8
      RVSA(I) = RVS(I)
 1201 CONTINUE
      GO TO 127
C
C*    CHECK L - ASH AFFINITY FOR ACID                                    *
 1202 GO TO (121,123), L
C
C*    RA237 IS LOG RESISTIVITY AS A FUNCTION OF SO3 CONCENTRATION        *
C*    AT RECIPROCAL TEMPERATURE = 2.37                                   *
C*    RAT IS LOG RESISTIVITY AS A FUNCTION OF SO3 CONCENTRATION          *
C*    AND TEMPERATURE                                                    *
C*    ADJUST RAT FOR THE EFFECT OF E                                     *
C*    RA IS RESISTIVITY AS A FUNCTION OF SO3 CONCENTRATION               *
C*    AND TEMPERATURE                                                    *
C
  121 RA237 = 12.9676 - (0.3075*SO3)
      DO 122  I=1,8
      RAT = RA237 + (10.1048*(2.37-TEMP(I)))
      RAT = RAT - (E-2.0)*SE
      RA(I) = 10.0**RAT
  122 CONTINUE
      GO TO 125
C
  123 RA237 = 12.1612 - (0.3712*SO3)
      DO 124  I=1,8
      RAT = RA237 + (5.6673*(2.37-TEMP(I)))
      RAT = RAT - (E-2.0)*SE
      RA(I) = 10.0**RAT
  124 CONTINUE
C
C*    RVSA IS RESISTIVITY RESULTING FROM THE COMBINATION OF THE          *
C*    RESISTIVITY AS A FUNCTION OF ACID CONCENTRATION AND THE            *
C*    RESISTIVITY RESULTING FROM THE PREVIOUS COMBINATION OF             *
C*    VOLUME AND SURFACE RESISTIVITIES USING THE EXPRESSION              *
C*    FOR PARALLEL RESISTANCES                                           *
  125 DO 126  I=1,8
      RVSA(I) = RVS(I)*RA(I)/(RVS(I)+RA(I))
  126 CONTINUE
C
C*    PRINT                                                              *
  127 WRITE (3,9)
    9 FORMAT (' TEMP 1000/T(K)',2X,'DEG K',2X,'DEG C',2X,'DEG F',3X,
     *   'RHO(VS)',3X,'RHO(VSA)'/ 1X.14('-'),2X,5('-'),2X,5('-'),2X,
     *   5('-'),3X,7('-'),3X,8('-'))
C
      DO 130  I=1,8
      IF (I .GE. 7) GO TO 128
      WRITE (3,13) TEMP(I),KT(I),ICT(I),IFT(I),RVS(I),RVSA(I)
   13 FORMAT (1X,0PF8.1,5X,3(4X,I3),3X,1PE8.1,3X,1PE8.1)
      GO TO 130
  128 WRITE (3,18) TEMP(I),KT(I),ICT(I),IFT(I),RVS(I)
   18 FORMAT (1X,0PF8.1,5X,3(4X,I3),3X,1PE8.1,7X,'**')
  130 CONTINUE
C
      WRITE (3,19)
   19 FORMAT (///' **  EXISTING EXPERIMENTAL DATA DO NOT JUSTIFY ',
     *   'COMPUTATIONS'/ 5X,'AT TEMPERATURES LOWER THAN 144 DEGREES C.',
     *   ////' NOTE: BECAUSE THE PREDICTED RESISTIVITY VALUES ARE ',
     *   'VERY'/ ' SENSITIVE TO SEVERAL FLUE GAS AND ASH COMPOSITIONAL',
     *   ' FACTORS,'/ ' ONE MUST EXERCISE GREAT CARE IN THE SELECTION ',
     *   'AND PREPARATION'/ ' OF COAL AND ASH SAMPLES. FURTHERMORE, ',
     *   'THE QUALITY OF THE'/ ' QUANTITATIVE CHEMICAL ANALYSIS WORK ',
     *   'IS OF GREAT IMPORTANCE.'/ ' IN ESTABLISHING THIS PROGRAM, ',
     *   'THE AS-RECEIVED, ULTIMATE COAL'/ ' ANALYSES WERE OBTAINED',
     *   ' USING ASTM D3176 PROCEDURE, AND THE'/ ' COAL ASH WAS ',
     *   'PRODUCED USING ASTM D271 PROCEDURE FOLLOWED BY'/ ' A SECOND',
     *   ' IGNITION AT 1050 DEGREES C + OR - 10 DEGREES C IN'/
     *   ' STILL AIR FOR 10 TO 12 HOURS.')
C
      GO TO 5
C
C*    SKIP TO TOP OF PAGE AND STOP
  999 WRITE (3,17)
   17 FORMAT ('1')
      STOP
      END
```

Table VI

```
PAGE 1         BASIC PROGRAM FOR RESISTIVITY PREDICTION                     27 AUG 1979

10 REM          ***** PROGRAM PREDRES *******
        BASIC PROGRAM WRITTEN IN TRS-80 DISK BASIC 32K RAM
   RESISTIVITY PREDICTION BASED ON WORK DONE BY
20 REM ROY BICKELHAUPT OF SOUTHERN RESEARCH
30 REM  BASIC PROGRAM (PREDRES) BY L.E. SPARKS
40  CLS:PRINT"RESISTIVITY PREDICTION":POKE 16425,0
50 LPRINT TAB(10)"RESISTIVITY PREDICTION BASED ON WORK DONE BY"
60 LPRINT TAB(10) "DR. ROY BICKELHAUPT OF SOUTHERN RESEARCH INSTITUTE"
70 LPRINT TAB(10) "BASIC PROGRAM BY DR. L.E.SPARKS PARTICULATE TECHNOLOGY BRANCH":
LPRINT TAB(10)"INDUSTRIAL ENVIRONMENTAL RESEARCH LAB RESEARCH TRIANGLE PARK NC EPA";
CHR$(10);TAB(25);"VERSION 1 MAY 1,1979"
80 DIM U$(7),AS$(11)
90 DIM XI(7),WT(7),XO(5),XD(5),O2(7),DA(7),WE(5),DR(5)
100 DIM XM(7),X0(11),WP(11),XW(11),XF(11),XP(11),XE(11),TE(8)
110 DIM KT(8),R(8),PE(11),CT(8),RV(8),RT(8),RS(8),RA(8),FT(8),S1(2)
120 DIM YC(2),SW(2)
130 REM THE FOLLOWING TWO FUNCTIONS ROUND TO NEAREST .001 AND .1
140 DEF FNR3(X)=INT(X*1000 +.5)/1000
150 DEF FNR1(X)=INT(X*10 +.5)/10
160 REM READ  TEMPERATURES FOR WHICH RESISTIVITY IS TO BE CALCULATED FROM DATA STATEMENT
170 REM TE = 1000/T DEG K, TK=TEMPERATURE DEG K,CT TEMPERATURE
DEG C,FT TEMPERATURE DEG F,KT TEMPERATURE DEG K INTEGER FORM
180 DEFINT K,I
190 FOR I=1 TO 8
200 READ TE(I),TK(I),CT(I),FT(I),KT(I)
210 NEXT I
220 REM READ MOLES OF O2 (XO) AND DRY AIR (XD) REQUIRED FOR COMBUSTION OF C,H2,O2,N2,S IN FUEL
230 FOR I=1 TO 5
240 READ XO(I),XD(I)
250 NEXT I
260 REM READ MOLECULAR WEIGHTS WT OF C,H2,O2,N2,S,AND H2O FROM DATA STATEMENT
270 FOR I=1 TO 6
280 READ WT(I)
290 NEXT I
300 REM READ % CATIONS FOR REPORTED ASH OXIDES
310 FOR I=1 TO 11
320 READ PE(I)
330 NEXT I
340 REM READ MOLECULAR WEIGHTS OF REPORTED ASH OXIDES
350 FOR I=1 TO 11
360 READ XW(I)
370 REM READ STRINGS FOR LABLES ** ALL READS ARE FROM DATA STATEMENTS
380 NEXT I
390 FOR I=1 TO 7:READ U$(I):NEXT I
400 FOR I=1 TO 11:READ AS$(I):NEXT I
```

Table VI (cont'd)

```
PAGE 2          BASIC PROGRAM FOR RESISTIVITY PREDICTION                    27 AUG 1979

410 S1(1)=-2.233348:S1(2)=-2.06184:YC(1)=24.807004:YC(2)=22.6416
420 SW(1)=.128:SW(2)=.2029
430 CX=130/100:XC=LOG(2.5)/LOG(10)
440 SV=4.3345*1000:XK=7.3894/10000.
450 X1=2.3033*1000:T=385:SE=.03
460 S3=0.:SO=0.:WA=0.
470 ES=.03:REM ES IS THE  CORRECTION FACTOR FOR  E  FIELD
480 LPRINT CHR$(10),CHR$(10),CHR$(10)
490 INPUT" NAME OF PLANT ";A$
500 INPUT"NAME OF COAL";B$
510 PRINT" PLANT NAME IS ";A$: REM CHECK TO SEE IF DATA ARE OK
520 PRINT" COAL NAME IS ";B$
530 INPUT"IS  THIS CORRECT Y OR N ";YY$
540 IF YY$="Y" THEN 560
550 PRINT"REENTER INCORRECT DATA":GOTO 490
560 LPRINT "PLANT NAME IS ";A$;"    COAL NAME IS ";B$
570 PRINT" INPUT ULTIMATE COAL ANALYSIS"
580 FOR I=1 TO 7
590           PRINT U$(I),XI(I);" PRESENT VALUE %":INPUT XI(I)
600 NEXT I
610 PRINT"ULTIMATE ANALYIS"
620 FOR I=1 TO 7
630           PRINT U$(I),XI(I)
640 NEXT I
650 INPUT"IS THIS CORRECT Y OR N";Y$
660 IF Y$="N" GOTO 670 ELSE GOTO 690
670 PRINT "REENTER ANY INCORRECT DATA":GOTO 580
680 REM THE FOLLOWING DATA ENTRIES ARE OPTIONAL IF 0 IS ENTERED THE PROGRAM WILL CALCULATE
690 INPUT"OPTIONAL INPUT IF INPUT 0 PROGRAM WILL CALCULATE
ENTER H2O IN GAS %";WA
700 PRINT"OPTIONAL INPUT. PRESS ENTER AND PROGRAM WILL CALCULATE
ENTER -1 IF DESIRE 0":
INPUT"ENTER SO2 IN PPM";SO
710 INPUT"OPTIONAL INPUT IS 0 INPUT PROGRAM WILL CALCULATE SO3 AS 0.004*SO2 ENTER PPM SO3";S3
720 INPUT"OPTIONAL INPUT IF ENTER 0 PROGRAM WILL CALCULATE ENTER ELECTRIC FIELD KV/CM";E
730   PRINT"ENTER ASH ANAYSIS"
740   FOR I=1 TO 11
750         PRINT AS$(I),X0(I);"PRESENT VALUE":INPUT X0(I)
760 IF E=0. THEN E =10
770   NEXT I
780 FOR I=1 TO 11
790         PRINT AS$(I),X0(I)
800 NEXT I
```

Table VI (cont'd)

```
PAGE 3         BASIC PROGRAM FOR RESISTIVITY PREDICTION                    27 AUG 1979

810 INPUT"IS THIS CORRECT ASH ANALYSIS Y OR N";Y$
820 IF Y$="N" THEN GOTO 730
830 REM CHECK TO SEE IF PROGRAM IS TO CALCULATE H20 AND SO2
840 IF WA<>0 AND SO<>0 GOTO 1110
850 REM SUM COAL ANALYSIS
860 S=0.
870 FOR I=1 TO 7
880         S=S+XI(I)
890 NEXT I
900 REM CHECK TO SEE IF SUM OF ASH ANALYSIS IS 100%
910 IF S =100 GOTO 970
920 REM NORMALIZE ASH ANALYSIS
930 FOR I=1 TO 7
940        XI(I)=XI(I)/S*100
950 NEXT I:S=100
960 REM CALCULATE AND SUM MOLES-MOLES =% MOLECULAR WEIGHT
970 SU=0.
980 FOR I= 1 TO 6
990         XM(I)=XI(I)/WT(I)
1000        XM(I) = FNR3(XM(I))
1010       SU=SU+XM(I)
1020 NEXT I
1030 REM CALCULATE AND SUM MOLES OF O2 AND DRY AIR REQUIRED FOR COMBUSTION AT 100% TOTAL AIR
1040 S0=0. :SD=0.
1050 FOR I= 1 TO 5
1060       IF I=4 GOTO 1090
1070       O2(I)=FNR3(XM(I)*XO(I)):DA(I)=FNR3(XM(I)*XD(I))
1080       S0=S0+O2(I):SD=SD+DA(I)
1090 NEXT I
1100 REM PRINT COMBUSTION REQUIREMENTS
1110 LPRINT"                                                   REQUIRED FOR COMBUSION"
1120 LPRINT"                                                        MOLES/100LB FUEL"
1130 LPRINT"        AS RECEIVED           MOLES PER           AT 100%TOTAL AIR"
1140 LPRINT"      ULTIMATE COAL       100LBS FUEL               O2          DRY AIR"
1150   FOR I= 1 TO 6
1160       LPRINT U$(I);TAB(10);XI(I);TAB(30);XM(I);TAB(50);O2(I),TAB(90);DA(I)
1170   NEXT I
1180 LPRINT"ASH      ";XI(7)
1190 LPRINT"SUM      ";S,"           ",SU,S0,SD
1200 REM CALCULATE MOLES O2 AND DRY AIR REQUIRED FOR 30% EXCESS AIR
```

Table VI (cont'd)

```
PAGE 4          BASIC PROGRAM FOR RESISTIVITY PREDICTION                     27 AUG 1979

1210 XS=FNR3(CX*S0)
1220 XD=FNR3(CX*SD)
1230 XA=XD-SD:XO=XS-S0
1240 LPRINT"---------------------------------------------------------------------------------"
1250 LPRINT"                                  REQUIRED FOR COMBUSTION"
1260 LPRINT"                                   MOLES/100 LB FUEL"
1270 LPRINT"                                    @30%EXCESS AIR"
1280 LPRINT"                                      O2     DRY AIR"
1290 LPRINT"O2 AND AIR*130/100 TOTAL          ";TAB(35);XS;TAB(45);XD
1300 LPRINT"EXCESS AIR";TAB(45);XA
1310 LFRINT"EXCESS O2    ";TAB(35);XO
1320 REM CALCULATE PRODUCTS OF COMBUSTION ****
1330 XM(2)=XM(2)+XM(6)+(XD*29*.013)/18.
1340 XM(3)=XM(5):XM(4)=XM(4)+(XD*.79)
1350 XM(5)=XO
1360 REM CALCULATE % BY VOLUME - WET BASIS
1370 SE=0.
1380 FOR I = 1 TO 5
1390        SE=SE+XM(I)
1400 NEXT I
1410 REM CALCULATE % BY VOLUME DRY BASIS
1420 SD =SE-XM(2)
1430 FOR I =1 TO 5
1440          WE(I)=FNR3(XM(I)/SE*100)
1450          DR(I)=FNR3(XM(I)/SD*100)
1460 NEXT I
1470 DR(2)=0.
1480 LPRINT"--------------------------------------------------------------"
1490 LPRINT"          ***** PRODUCTS OF COMBUSTION *****""
1500 LPRINT"     TOTAL"
1510 LPRINT"     MOLES/100         % BY VOL            % BY VOL"
1520 LPRINT"     FUEL             WET BASIS           DRY BASIS"
1530 LPRINT"CO2   ";XM(1);TAB(23);WE(1);TAB(44);DR(1):
LPRINT"H20    ";XM(2);TAB(23);WE(2)TAB(44);DR(2)
1540 LPRINT"SO2   ";XM(3);TAB(23)WE(3);TAB(44);DR(3):
LPRINT"N2     ";XM(4);TAB(23);WE(4);TAB(44);DR(4)
1550 LPRINT"O2     ";XM(5);TAB(23);WE(5);TAB(44);DR(5):
LPRINT"SUM WET  ";SE:LPRINT"SUM DRY   ";SD
1560 REM CALCULATE H20,SO2,SO3,AND INSERT DEFAULT ELECTRIC FIELD
1570 IF WA =0. THEN WA =WE(2)
1580 IF SO=0. THEN SO=DR(3)*10000
1590 IF SO=-1 THEN SO=0
1600 IF S3=0. THEN S3=0.004*SO
```

Table VI (cont'd)

```
PAGE 5          BASIC PROGRAM FOR RESISTIVITY PREDICTION                    27 AUG 1979

1610 REM ROUND H20 AND SO3 TO NEAREST .1
1620 WA=FNR1(WA):S3=FNR1(S3)
1630 LPRINT CHR$(10),CHR$(10),CHR$(10)
1640 LPRINT "H20 ";WA;" %";CHR$(10);"SO2  ";SO;" PPM";CHR$(10);"SO3 ";S3;" PPM"
1650 LPRINT "ELECTRIC FIELD ";E;" KV/CM"
1660 SX=0
1670 FOR I = 1 TO 11
1680          SX=SX+X0(I)
1690 NEXT I
1700 REM NORMALIZE AND SUM ASH ANALYSIS
1710 SA=0
1720 FOR I= 1 TO 11
1730           WP(I)=(X0(I)/SX)*100
1740          SA= SA + WP(I)
1750 NEXT I
1760 REM CALCULATE AND SUM MOLE FRACTION
1770 SZ=0
1780 FOR I = 1 TO 11
1790           XF(I)=WP(I)/XW(I)
1800         SZ = SZ + XF(I)
1810 NEXT I
1820 REM CALCULATE AND SUM ATOMIC CONCENTRATIONS OF CATIONS XE(I)
1830 SB=0
1840 FOR I = 1 TO 11
1850            XP(I)=XF(I)/SZ
1860           XE(I) = XP(I)*PE(I)
1870            SB=SB+XE(I)
1880 NEXT I
1890 SL=INT((XE(1)+XE(2))*100 +.5)/100:CM=FNR1(XE(4)+XE(5))
1900 XE(6)=FNR1(XE(6))
1910 XE(3)=INT(XE(3)*100+.5)/100
1920 L =1:IF CM>3.5 AND XE(3)<1. L=2
1930 LPRINT CHR$(12):INPUT"PRESS ENTER FOR NEXT PAGE";QW
1940 LPRINT TAB(28)"CORRECTED"
1950 LPRINT TAB(7) "ASH";TAB(32) "ASH";TAB(50) "ATOMIC"
1960 LPRINT TAB(5)"ANALYSIS";TAB(30)"ANALYSIS";TAB(47)"CONCENTRATION"
1970 FOR I=1 TO 11
1980 LPRINT AS$(I);TAB(6);X0(I);TAB(30);WP(I);TAB(49);XE(I)
1990 NEXT I
2000 LPRINT"SUM ";SX,"   ",SA,SB
```

Table VI (cont'd)

```
PAGE 6         BASIC PROGRAM FOR RESISTIVITY PREDICTION                    27 AUG 1979

2010 LPRINT"SUM OF LITHIUM AND SODIUM ATOMIC CONCENTRATIONS     ";SL
2020 LPRINT"SUM OF MAGNESIUM AND CALCIUM CONCENTRATIONS         ";CM
2030 LPRINT"IRON ATOMIC CONCENTRATION                           ";XE(6)
2040 LPRINT"POTASSIUM ATOMIC CONCENTRATION                      ";XE(3)
2050 R6=8. 9434-1. 8916*LOG(SL)/LOG(10)-. 9696*LOG(XE(6))/LOG(10)+1. 237*(LOG(CM)/LOG(10)-XC)
2060 REM BEGIN CALCULATION OF RESISTIVITY
2070 REM R6 IS THE RESISTIVITY AT 1000/T K =1. 6 BASED ON
EXPERIMENTAL CORRELATION
2080  REM OF RESISTIVITY AS A FUNCTION OF ASH COMPOSITION
2090 REM R0 IS THE PRE-EXPONENTIAL TERM IN THE ARRHENIUS EQUATION
2100 R0=R6-SV/625
2110 REM RV IS THE RESISTIVITY DEFINED BY THE ARRHENIUS EQUATION
2120 FOR I = 1 TO 8
2130           RV(I) = R0 + SV/TK(I)
2140          RV(I)=RV(I)-(E-2)*ES
2150          RV(I)=10.[RV(I)
2160 NEXT I
2170 FOR I = 1 TO 2
2180          J = I + 6
2190         RS=EXP(S1(I)*LOG(SL) +YCEPT(I))
2200         RW=LOG(RS)/LOG(10)-(WA-9)*SW(I)
2210         RC=RW-(E-2)*ES
2220         RT(J)=10.[RC
2230 NEXT I
2240 REM R1 IS THE PRE-EXPONENTIAL TERM IN THE DOUBLE EXPONENTIAL SURFACE RESISTIVITY EQUATION
2250 R1= RT(7)/EXP(-WA*XK*EXP(X1/T))
2260 REM RT IS THE SURFACE RESISTIVITY
2270 FOR I = 1 TO 6
2280          RT(I)=R1*EXP(-WA*XK*EXP(X1/TK(I)))
2290 NEXT I
2300 REM RS(I) IS THE COMBINED RESISTIVITY DUE TO PARALLEL
COMBINATION OF SURFACE AND VOLUME RESISTIVITY
2310 FOR I=1 TO 8
2320         RS(I)=RV(I)*RT(I)/(RT(I)+RV(I))
2330 NEXT I
2340 REM CHECK FOR AFFINITY OF ASH FOR ACID
2350 REM CALCULATE RESISTIVITY IN PRESENCE OF SO3
2360 IF L=2 GOTO 2450
2370 R7=12. 9675-(. 3075*S3)
2380 FOR I = 1 TO 8
2390          RT=R7 +(10. 1048*(2. 37-TE(I)))
2400        RT=RT- (E-2. 0)*ES
```

Table VI (cont'd)

```
PAGE 7          BASIC PROGRAM FOR RESISTIVITY PREDICTION                          27 AUG 1979

2410          RA(I)=10.[RT
2420 NEXT I
2430 REM TRANSFER TO CALCULATION OF COMBINED RESISTIVITY
2440 GOTO 2530
2450 R7=12.1612-(.3712*S3)
2460 FOR I = 1 TO 8
2470         RT = R7 +(5.6673*(2.37-TE(I)))
2480        RT= RT - (E - 2.0)*ES
2490         RA(I) = 10.[RT
2500 NEXT I
2510 REM CALCULATE COMBINED RESISTIVITY OF VOLUME AND SURFACE
2520 REM RESISTIVITY DUE TO SO3 IN PARALLEL
2530 FOR I = 1 TO 8
2540         R(I)=RS(I)*RA(I)/(RS(I)+RA(I))
2550 NEXT I
2560 REM ROUND RESISTIVITY
2570   FOR I=1 TO 8
2580         C=INT(LOG(RS(I))/LOG(10))
2590        RS(I)=FNR1(RS(I)/10[C): RS(I)=RS(I)*10[C
2600       C=INT(LOG(R(I))/LOG(10))
2610       R(I)=FNR1(R(I)/10[C):R(I)=R(I)*10[C
2620   NEXT I
2630 LPRINT CHR$(10),CHR$(10),"---------------------------------------------"
2640 LPRINT"TEMP 1000/T(K)   DEGK           DEGC            DEGF          RHO         RHO(S)"
2650 LPRINT"------------------------------------------------------------------------------------------"
2660 FOR I= 1 TO 8:IF I>6 GOTO 2680
2670 LPRINT TE(I),KT(I),CT(I),FT(I);"      ";RS(I);"      ";R(I):GOTO 2690
2680 LPRINT TE(I),KT(I),CT(I),FT(I);"      ";RS(I);"      **"
2690 NEXT I
2700 LPRINT CHR$(10)
2710 LPRINT "------------------------------------------------------------------------------------------"
2720 LPRINT CHR$(10)
2730 LPRINT CHR$(10)" RHO IS RESISTIVITY WITHOUT SO3 IN OHM-CM BUT WITH ";WA;" % WATER""
2740 LPRINT "RHO(S) IS THE RESISTIVITY WITH ";S3;" PPM OF SO3 IN OHM CM"
2750 LPRINT"**************************************************"
2760 LPRINT "**  NOTE !! EXISTING EXPERIMENTAL DATA DO NOT JUSTIFY"
2770 LPRINT"COMPUTATIONS AT TEMPERATURES LOWER THAN 144 DEGREE C"
2780 LPRINT "**************************************************"
2790 LPRINT"*** NOTE *** BECAUSE THE PREDICTED RESISTIVITY VALUES ARE"
2800 LPRINT" VERY! SENSITIVE TO SEVERAL FLUE GAS AND ASH COMPOSITIONAL"
```

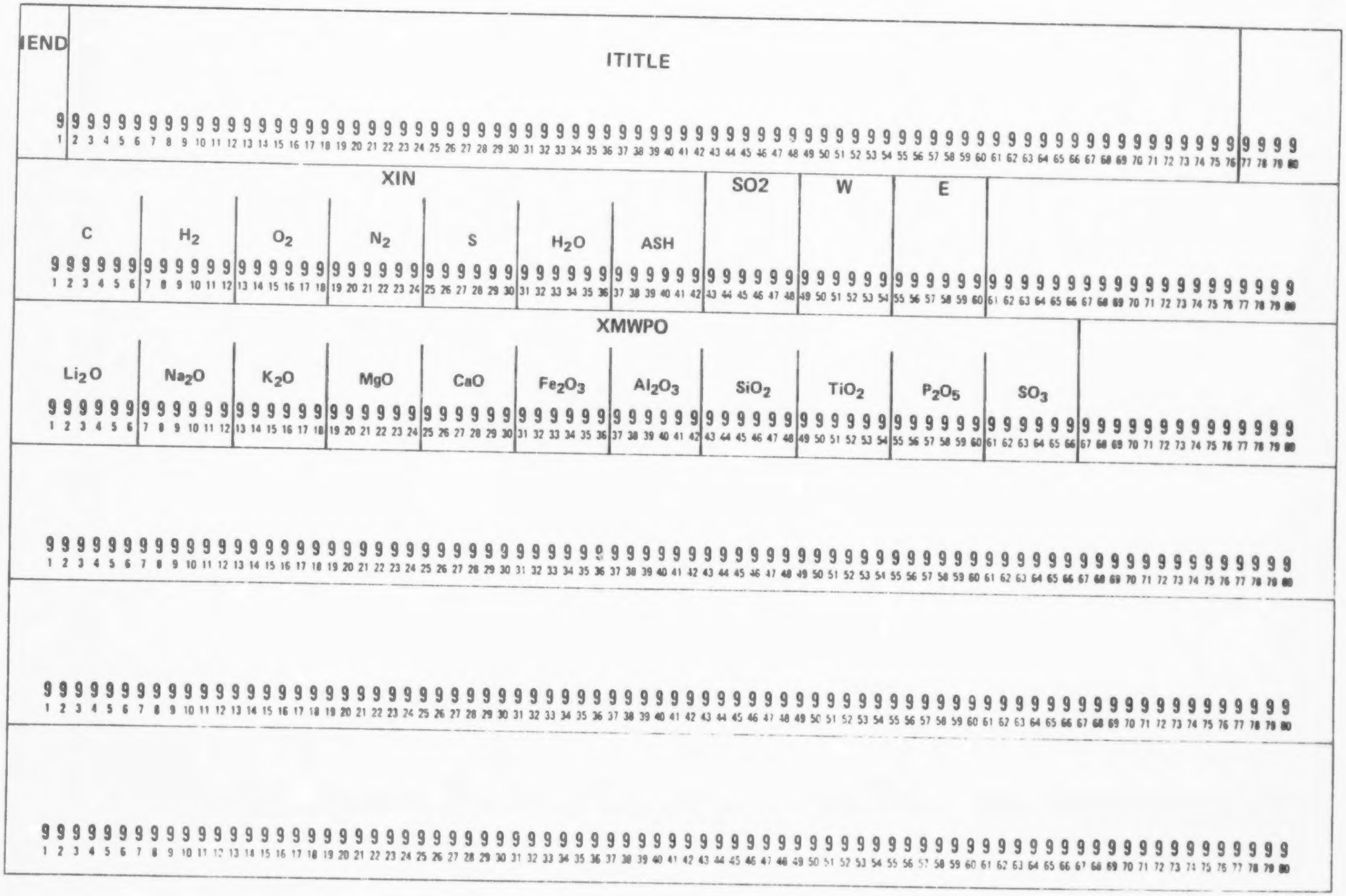
Table VI (concluded)

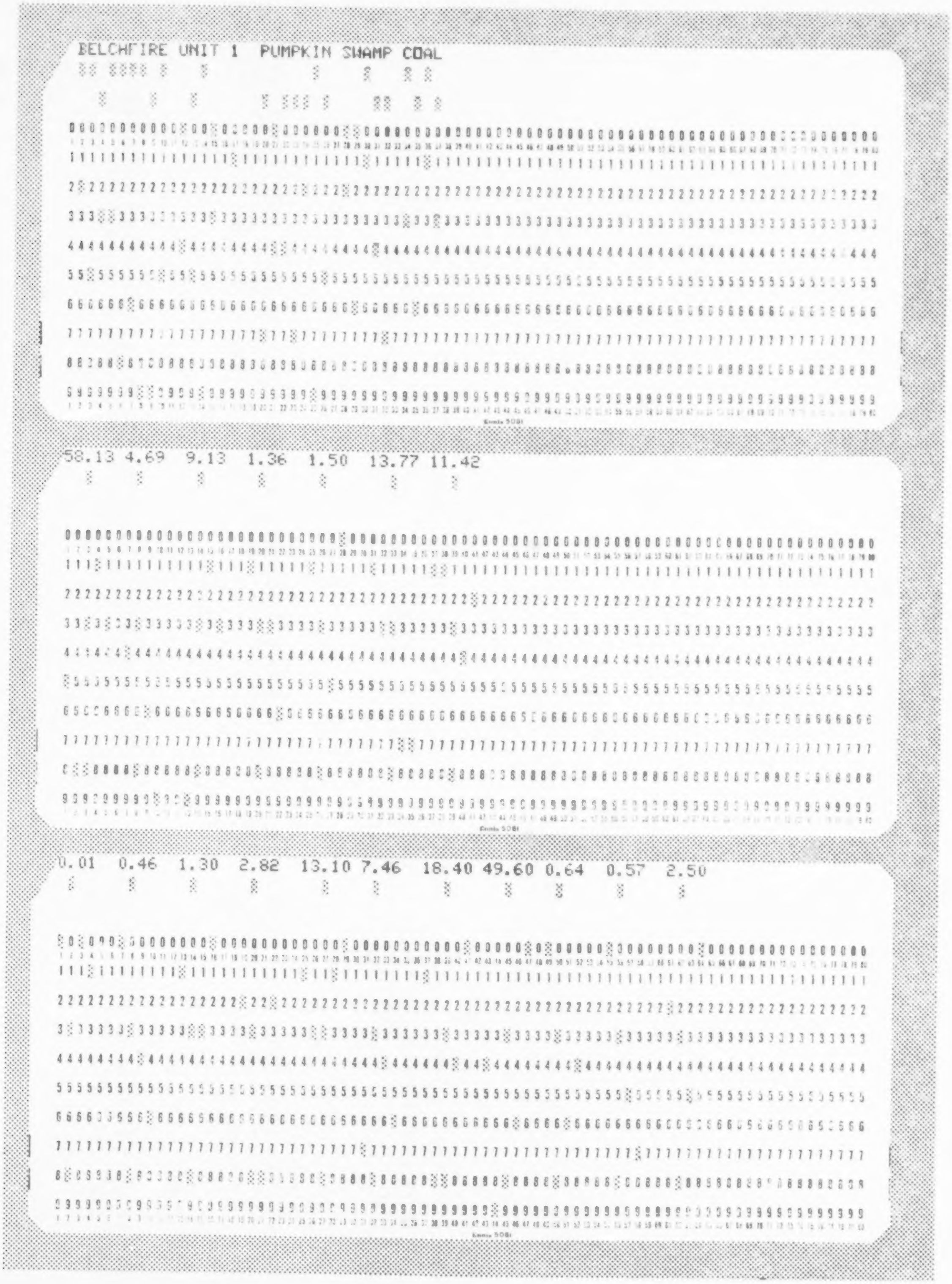
```
PAGE 8          BASIC PROGRAM FOR RESISTIVITY PREDICTION                    27 AUG 1979

2810 LPRINT"FACTORS ONE MUST EXCERCISE GREAT CARE IN THE SELECTION "
2820 LPRINT "AND PREPARATION OF COAL AND ASH SAMPLES***"
2830 LPRINT" THE QUALITY OF THE QUANTITATIVE CHEMICAL ANALYSIS WORK IS"
2840 LPRINT"OF GREAT IMPORTANCE**.  "
2850 LPRINT"IN ESTABLISHING THIS PROGRAM THE AS-RECEIVED ULTIMATE"
2860 LPRINT"COAL ANALYSES WERE OBTAINED USING ASTM D3176"
2870 LPRINT"COAL ASH WAS PRODUCED USING ASTM D271 PROCEDURE"
2880 LPRINT"FOLLOWED BY A SECOND IGNITION AT 1050 DEG C "
2890 LPRINT"+OR- 10 DEG C IN STILL AIR FOR 10 TO 12 HOURS"
2900 LPRINT"**************************************************"
2910 LPRINT CHR$(12)
2920 INPUT "ENTER 1 TO CALCULATE RESISTIVITY FOR DIFFERENT SO3";X
2930 IF X<>1 GOTO 2980
2940 INPUT"NEW SO3 CONCENTRATION IN PPM";S3
2950 LPRINT "RESISTIVITY FOR ";A$;" BURNING ";B$;" COAL WITH SO3 OF ";S3;" PPM"
2960 X=0
2970 GOTO 2360
2980 INPUT" DO YOU WANT TO CALCULATE RESISTIVITY FOR ANOTHER PLANT Y OR N";Y$
2990 IF Y$="Y" RUN
3000 STOP
3010 DATA 1.4,714,441,826,714
3020 DATA 1.6,625,352,666,625,1.8,556,283,541,556,2,500,227,441,500
3030 DATA 2.2,455,182,359,455,2.4,417,144,291,417
3040  DATA 2.6,385,112,233,385,2.8,357,84,183,357
3050 DATA 1,4.76,.5,2.38,-1.,-4.76,0.,0,1,4.76
3060 DATA 12.01,2.02,32,28.01,32.06,18.02
3070 DATA 66.66,66.66,66.66,50.,50.,40,40,33.33,33.33,28.57,25
3080 DATA 29.88,61.98,94.2,40.3,56.08,159.7,101.96,60.09,79.9,141.94,80.06
3090  DATA "C","H2","O2","N2","S","H2O","ASH"
3100  DATA"LI2O","NA2O","K2O","MGO","CAO","FE2O3","AL2O3","SIO2","TIO2","P2O5","SO3"
```

Figure 25.

MULTIPLE-CARD LAYOUT FORM


IEND
ITITLE
XIN
C
H_2
O_2
N_2
S
H_2O
ASH
SO2
W
E
XMWPO
Li_2O
Na_2O
K_2O
MgO
CaO
Fe_2O_3
Al_2O_3
SiO_2
TiO_2
P_2O_5
SO_3



BELCHFIRE UNIT 1 PUMPKIN SWAMP COAL

58.13 4.69 9.13 1.36 1.50 13.77 11.42

0.01 0.46 1.30 2.82 13.10 7.46 18.40 49.60 0.64 0.57 2.50

Figure 26. Example Data Input Cards

simply omitted from the data input. If one wants the resistivity predicted for some value of field strength other than 10 kV/cm, the field strength value desired is punched in for the variable E instead of leaving it blank. Also, in place of an as-received coal analysis (variable XIN on the second card), one can introduce known or assumed sulfur dioxide and environmental water concentrations for the variables SO2 and W respectively on the second card.

Table VII is the data printout for the FORTRAN computer program for predicting resistivity as a function of temperature. On the first page, the as-received ultimate coal analysis input data are shown along with the essential features of the calculation of combustion products using 30% excess air. At the bottom of the page, several of the parameters critical to the calculation of resistivity are tabulated: (1) the environmental water concentration in volume percent, 9.9%; (2) the sulfur dioxide concentration in dry volume ppm, 1350 ppm; (3) the sulfur trioxide concentration (sulfur dioxide x 0.004) in dry volume ppm, 5.4 ppm; and the field strength (E) to be used, 10 kV/cm.

Table VIII is the data printout for the BASIC program. On the top of the second page of Tables VII and VIII, the ash analysis input data are shown with the resultant values of cationic atomic concentration. This calculation was demonstrated in the preceding section. The atomic concentrations critical to the computation of resistivity are tabulated as: (1) lithium plus sodium, 0.35%; (2) magnesium plus calcium, 10.7%; (3) iron, 1.3% and (4) potassium, 0.65%. At the bottom of the page is a tabulation of temperature and resistivity. The resistivity values with the heading RHO (VS) are those resulting if the effect of sulfuric acid vapor is excluded, while the data headed RHO (VSA) are those resulting from the prediction including the effect of acid vapor.

Figure 27 presents in graphical form the predicted values of resistivity as a function of temperature with and without the effect of sulfuric acid vapor taken into account. These data were generated using a fictive coal and coal ash. Although the principal purpose of the technique is to predict resistivity from core bore samples of coal, one can obviously use it to generate information about the effect that various parameters have on resistivity.

Table VII

```
RESISTIVITY PREDICTION BASED ON WORK DONE BY
DR. ROY BICKELHAUPT OF SOUTHERN RESEARCH INSTITUTE.
THE RESEARCH WAS SPONSORED BY THE PARTICULATE
TECHNOLOGY BRANCH, INDUSTRIAL ENVIRONMENTAL RESEARCH
LABORATORY OF THE ENVIRONMENTAL PROTECTION AGENCY.
DR. L. E. SPARKS, PROJECT OFFICER.

BELCHFIRE UNIT 1  PUMPKIN SWAMP COAL


                                                 REQUIRED FOR COMBUSTION
                                                  MOLES/100 LB FUEL
        AS RECEIVED           MOLES PER           AT 100% TOTAL AIR
       ULTIMATE COAL           100 LB           -----------------------
         ANALYSIS               FUEL              O2          DRY AIR
       -------------         ---------          ------        -------
C          58.13               4.840            4.840         23.038
H2          4.69               2.322            1.161          5.526
O2          9.13               0.285           -0.285         -1.357
N2          1.36               0.049            0.000          0.000
S           1.50               0.047            0.047          0.224
H2O        13.77               0.764            0.000          0.000
ASH        11.42               0.000            0.000          0.000

SUM       100.00               8.307            5.763         27.431


                                          REQ FOR COMBUSTION
                                           MOLES/100 LB FUEL
                                            @30% EXCESS AIR
                                          ------------------
                                            O2      DRY AIR
                                          ------    -------
O2 AND AIR * 130/100 TOTAL                 7.492     35.660
EXCESS AIR                                            8.229
EXCESS O2                                  1.729


                    PRODUCTS OF COMBUSTION
            --------------------------------------
             TOTAL
            MOLES/100       % BY VOL       % BY VOL
            LB FUEL         WET BASIS      DRY BASIS
            ---------       ---------      ---------
CO2            4.840         12.516          13.894
H2O            3.833          9.912           0.000
SO2            0.047          0.122           0.135
N2            28.220         72.979          81.008
O2             1.729          4.471           4.963
SUM WET       38.669
SUM DRY       34.836


H2O              9.9
SO2             1350
SO3              5.4

E                 10
```

Table VII. cont'd.

	ASH ANALYSIS	CORRECTED ASH ANALYSIS	ATOMIC CONCENTRATION
LI2O	0.01	0.01	0.016
NA2O	0.46	0.47	0.348
K2O	1.30	1.34	0.647
MGO	2.82	2.91	2.462
CAO	13.10	13.52	8.220
FE2O3	7.46	7.70	1.315
AL2O3	18.40	19.00	5.080
SIO2	49.60	51.21	19.361
TIO2	0.64	0.66	0.188
P2O5	0.57	0.59	0.081
SO3	2.50	2.58	0.549
SUM	96.86	100.00	38.267

SUM OF LITHIUM AND SODIUM ATOMIC CONCENTRATIONS	0.36
SUM OF MAGNESIUM AND CALCIUM ATOMIC CONCENTRATIONS	10.7
IRON ATOMIC CONCENTRATION	1.3
POTASSIUM ATOMIC CONCENTRATION	0.65

TEMP 1000/T(K)	DEG K	DEG C	DEG F	RHO(VS)	RHO(VSA)
1.4	714	441	826	2.2E+09	2.2E+09
1.6	625	352	666	1.6E+10	1.6E+10
1.8	556	283	541	1.1E+11	1.1E+11
2.0	500	227	441	6.3E+11	3.9E+11
2.2	455	182	359	1.2E+12	7.1E+10
2.4	417	144	291	7.3E+11	5.5E+09
2.6	385	112	233	2.6E+11	**
2.8	357	84	183	2.1E+10	**

** EXISTING EXPERIMENTAL DATA DO NOT JUSTIFY COMPUTATIONS AT TEMPERATURES LOWER THAN 144 DEGREES C.

NOTE: BECAUSE THE PREDICTED RESISTIVITY VALUES ARE VERY SENSITIVE TO SEVERAL FLUE GAS AND ASH COMPOSITIONAL FACTORS, ONE MUST EXERCISE GREAT CARE IN THE SELECTION AND PREPARATION OF COAL AND ASH SAMPLES. FURTHERMORE, THE QUALITY OF THE QUANTITATIVE CHEMICAL ANALYSIS WORK IS OF GREAT IMPORTANCE. IN ESTABLISHING THIS PROGRAM, THE AS-RECEIVED, ULTIMATE COAL ANALYSES WERE OBTAINED USING ASTM D3176 PROCEDURE, AND THE COAL ASH WAS PRODUCED USING ASTM D271 PROCEDURE FOLLOWED BY A SECOND IGNITION AT 1050 DEGREES C + OR - 10 DEGREES C IN STILL AIR FOR 10 TO 12 HOURS.

Table VIII

```
PAGE 9        BASIC PROGRAM FOR RESISTIVITY PREDICTION                    27 AUG 1979

         RESISTIVITY PREDICTION BASED ON WORK DONE BY
         DR. ROY BICKELHAUPT OF SOUTHERN RESEARCH INSTITUTE
         BASIC PROGRAM BY DR. L.E.SPARKS PARTICULATE TECHNOLOGY BRANCH
         INDUSTRIAL ENVIRONMENTAL RESEARCH LAB RESEARCH TRIANGLE PARK NC EPA
                      VERSION 1 MAY 1,1979


PLANT NAME IS BELCHFIRE 1    COAL NAME IS PUMPKIN SWAMP
                                           REQUIRED FOR COMBUSION
                                               MOLES/100LB FUEL
       AS RECEIVED          MOLES PER        AT 100%TOTAL AIR
      ULTIMATE COAL         100LBS FUEL        O2          DRY AIR
C          58.13              4.84            4.84          23.038
H2         4.69               2.322           1.161         5.526
O2         9.13               .285           -.285         -1.357
N2         1.36               .049            0             0
S          1.5                .047            .047          .224
H20        13.77              .764            0             0
ASH        11.42
SUM        100                 8.307          5.763         27.431
-----------------------------------------------------------------------
                              REQUIRED FOR COMBUSTION
                               MOLES/100 LB FUEL
                                @30%EXCESS AIR
                                  O2      DRY AIR
O2 AND AIR*130/100 TOTAL         7.492     35.66
EXCESS AIR                                 8.229
EXCESS O2                        1.729
--------------------------------------------------------
          ***** PRODUCTS OF COMBUSTION *****
     TOTAL
     MOLES/100          % BY VOL            % BY VOL
     FUEL               WET BASIS           DRY BASIS
CO2    4.84             12.516              13.894
H20     3.83288         9.912               0
SO2    .047             .122                .135
N2      28.2204         72.979              81.008
O2     1.729            4.471               4.963
SUM WET   38.6693
SUM DRY    34.8364


H20  9.9  %
SO2   1350  PPM
SO3  5.4  PPM
ELECTRIC FIELD  10  KV/CM
```

Table VIII (cont'd)

```
                                CORRECTED
        ASH                        ASH             ATOMIC
      ANALYSIS                  ANALYSIS       CONCENTRATION
LI2O   .01                      .0103242         .0156999
NA2O   .46                      .474912          .348163
K2O    1.3                      1.34214          .65
MGO    2.82                     2.91142          2.46221
CAO    13.1                     13.5247          8.21948
FE2O3  7.46                     7.70184          1.3
AL2O3  18.4                     18.9965          5.07995
SIO2   49.6                     51.2079          19.3609
TIO2   .64                      .660748          .18788
P2O5   .57                      .588478          .0887405
SO3    2.5                      2.58105          .549383
SUM  96.86                       100            38.2668
SUM OF LITHIUM AND SODIUM ATOMIC CONCENTRATIONS      .36
SUM OF MAGNESIUM AND CALCIUM CONCENTRATIONS          10.7
IRON ATOMIC CONCENTRATION                            1.3
POTASSIUM ATOMIC CONCENTRATION                       .65

                 --------------------------------------------------
TEMP 1000/T(K)   DEGK          DEGC          DEGF          RHO          RHO(S)
----------------------------------------------------------------------------------
 1.4             714           441           826           2.2E+09      2.2E+09
 1.6             625           352           666           1.6E+10      1.6E+10
 1.8             556           283           541           1.1E+11      1.1E+11
 2               500           227           441           6.3E+11      3.9E+11
 2.2             455           182           359           1.2E+12      7.1E+10
 2.4             417           144           291           7.3E+11      5.5E+09
 2.6             385           112           233           2.6E+11      **
 2.8             357           84            183           2.1E+10      **
----------------------------------------------------------------------------------
 RHO IS RESISTIVITY WITHOUT SO3 IN OHM-CM BUT WITH  9.9  % WATER
RHO(S) IS THE RESISTIVITY WITH  5.4  PPM OF SO3 IN OHM CM
*************************************************
**  NOTE !! EXISTING EXPERIMENTAL DATA DO NOT JUSTIFY
COMPUTATIONS AT TEMPERATURES LOWER THAN 144 DEGREE C
***********************************************
*** NOTE *** BECAUSE THE PREDICTED RESISTIVITY VALUES ARE
 VERY! SENSITIVE TO SEVERAL FLUE GAS AND ASH COMPOSITIONAL
FACTORS ONE MUST EXCERCISE GREAT CARE IN THE SELECTION
AND PREPARATION OF COAL AND ASH SAMPLES***
 THE QUALITY OF THE QUANTITATIVE CHEMICAL ANALYSIS WORK IS
OF GREAT IMPORTANCE**.
IN ESTABLISHING THIS PROGRAM THE AS-RECEIVED ULTIMATE
COAL ANALYSES WERE OBTAINED USING ASTM D3176
COAL ASH WAS PRODUCED USING ASTM D271 PROCEDURE
FOLLOWED BY A SECOND IGNITION AT 1050 DEG C
+OR- 10 DEG C IN STILL AIR FOR 10 TO 12 HOURS
*************************************************
```

SYM	PRINT OUT	NAME	C/P	PR.	H_2O	O_2	CO_2	SO_2	SO_3	P%	E, kV/cm	mmd, µm	d, g/cc	DATE
○	RHO(vs)	BELCH FIRE UNIT 1	–	–	9.9	5.0	13.9	0	0	–	10	–	–	–
△	RHO(vsa	PUMPKIN SWAMP COAL	–	–	9.9	5.0	13.9	1350	5.4	–	10	–	–	–

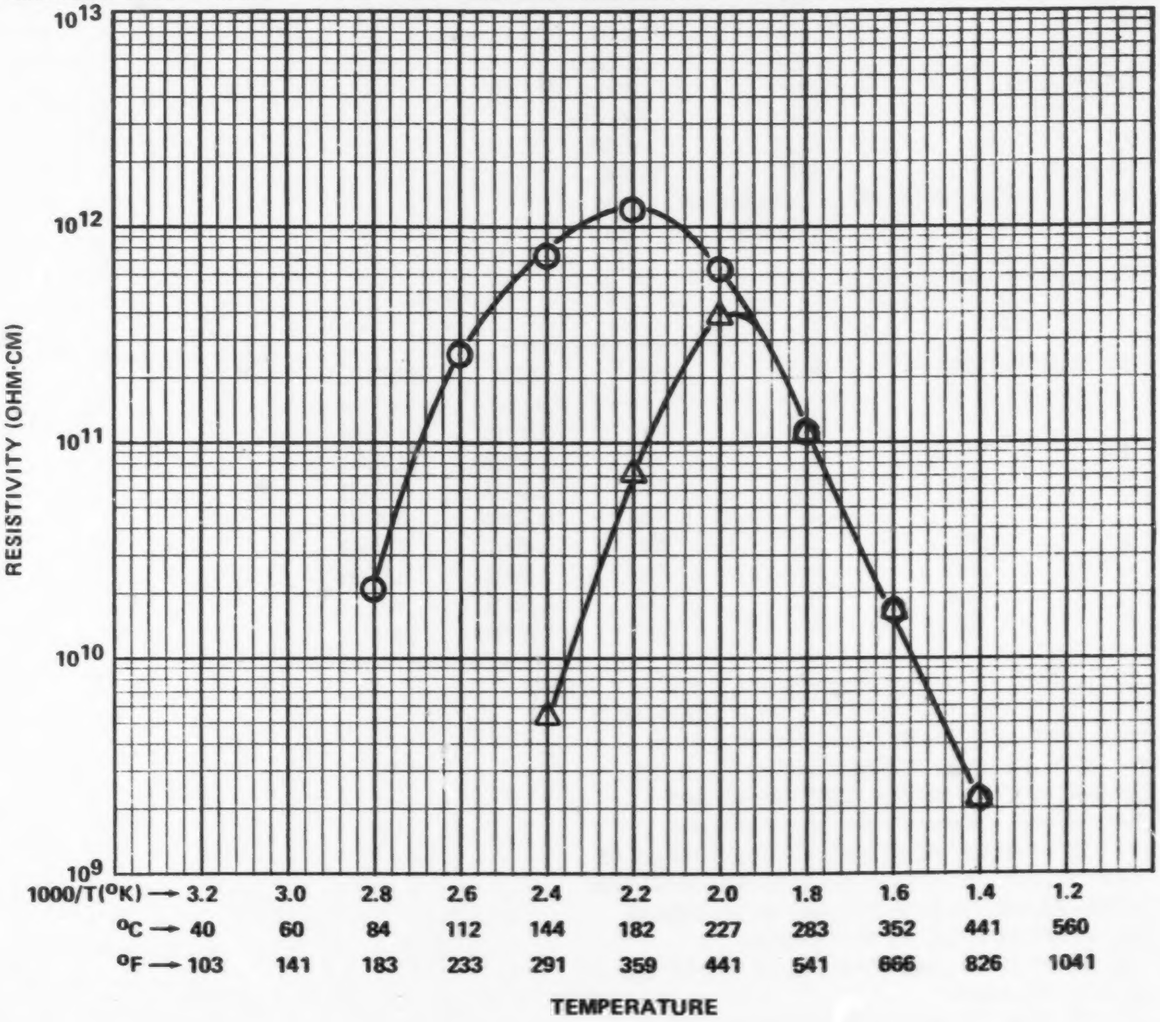


Figure 27. Predicted resistivity for the fictive coal and coal ash used to illustrate the computer program.

SECTION 9

PREDICTED RESISTIVITY PROOF TEST

In the preceding sections experimental data have been presented to quantitatively relate resistivity to the principal fly ash and flue gas compositional factors that influence this property. Finally, these relationships were used to predict resistivity as a function of temperature utilizing input data acquired from the ultimate analysis of a coal and the compositional analysis of the respective coal ash.

The accuracy of resistivity predictions made in the above manner was tested using data mainly acquired from another research project that required significant field testing.[23] The objective of the proof test was to compare predicted resistivity values with those values determined in the laboratory and *in situ* using a point-plane resistivity probe. Furthermore, these data were compared with mass train efficiency information and the current density of the outlet field of the precipitator.

During a relatively short time period (several hours) while the boiler and the precipitator were operating in a normal full-load manner, the following data and samples were simultaneously taken: coal sample, fly ash sample, *in situ* resistivity data, mass train efficiency data, secondary current and voltage data, and the flue gas analysis at the precipitator inlet. The coal sample was used to obtain the as-received ultimate coal analysis and to produce the coal ash for chemical analysis. The fly ash sample was subjected to chemical analysis and was used to determine the laboratory resistivity data. Laboratory resistivity values were measured in an environment simulating the *in situ* environment with respect to temperature and the concentrations of water vapor and sulfur trioxide.

The field test data and samples from six power stations were used. Three stations were burning coals from the western part of the United States. Two cold-side and one hot-side precipitators were in use at these stations. A similar situation existed for the three stations burning coal from the eastern part of the United States with the exception of the prerequisite that one of the cold-side units was collecting ash produced from a "cleaned" coal.

For each station, Table IX records the field test date, the size of the unit tested, the specific collection area of the precipitator and the analysis of the coal being burned at the time of interest. The W or E following the station number indicates whether the station was burning western or eastern coal respectively. The table conveys the variation in station and precipitator size and the coal quality.

In Table X the chemical analyses for fly ash and coal ash for each station are shown. The coal ash was analyzed after the ashing procedure previously described in detail was executed. Soluble sulfate ($SO_4^=$) and loss on ignition were determined on separate fly ash specimens. The remainder of the ash from the loss on ignition test was used to determine the chemical composition of fly ash.

Also in Table X, the in situ flue gas composition is compared with the composition calculated from the stoichiometric combustion of the coal using 30% excess air. It was previously stated that the predicted value for sulfur trioxide was arbitrarily taken as 0.4% of the sulfur dioxide value. With respect to the measured flue gas values, the sulfur dioxide and sulfur trioxide values are usually averages and ranges of values respectively depending on the availability of field test data taken during a time period of two to eight hours.

Comparison of the chemical compositions of fly ash with the respective coal ash compositions shows little difference between the values that are specifically significant in the prediction of resistivity. These of course, include the elements lithium, sodium, magnesium, calcium and iron. Furthermore, the entire weight percent analysis of the coal ash is similar enough to the respective fly ash analysis that one would not find a significant difference between resistivity data predicted from fly ash or coal ash for the stations evaluated.

With respect to the prediction of resistivity, the principal flue gas species are sulfur trioxide and water vapor. The in situ and predicted values for these environmental factors can also be compared in Table X. For the six stations examined, the water concentration was under-predicted three times and over-predicted three times. The greatest deviation was a predicted concentration 30% greater than the measured value. On the average, the predicted concentration was 5% greater than the measured value. Typically, a predicted value of 9.5 volume percent would relate to a 9.0 volume percent measured value, an insignificant difference. Under the usual cold-side precipitator conditions, a 30% error in water concentration could cause a factor of two error in predicted resistivity.

Table IX. Predicted Resistivity Proof Check
General Information and Coal Analyses for Six Power Stations

STATION NUMBER	1(W)	3(E)	4(E)	5(W)	7(E)	13(W)
TEST DATE	7 AUG 75	2 MAR 76	27 APR 76	5 OCT 76	17 SEPT 76	21 JULY 77
UNIT SIZE, MW	135	122	271	508	350	800
SCA OF ESP, $m^2/m^3/sec$	98.8	50.2	76.4	117.2	33.3	60.2
$ft^2/ft^3/min$	504	256	390	598	170	307
COAL ANALYSIS						
AS-RECEIVED						
PROXIMATE, wt. %						
Moisture	13.94	10.84	6.22	19.91	11.68	12.34
Volatile Matter	37.78	33.99	30.73	26.48	31.06	37.81
Fixed Carbon	43.07	43.94	50.20	42.16	46.36	40.59
Ash	5.21	11.23	12.85	11.45	10.90	9.27
Sulfur	0.41	2.05	0.95	0.43	0.81	0.48
Btu	10,557	11,050	11,903	9,104	12,011	10,630
AS-RECEIVED						
ULTIMATE, wt. %						
Carbon	59.41	62.44	64.75	52.01	65.22	60.58
Hydrogen	4.24	3.95	4.11	3.53	3.87	4.16
Oxygen	15.33	8.27	9.42	11.55	6.21	11.78
Nitrogen	1.46	1.25	1.69	1.02	1.21	1.39
Sulfur	0.41	2.02	0.96	0.53	0.91	0.48
Moisture	13.94	10.84	6.22	19.91	11.68	12.34
Ash	5.21	11.23	12.85	11.45	10.90	9.27

Table X. Predicted Resistivity Proof Check
Fly Ash, Coal Ash, and Flue Gas Compositions for Six Power Stations

STATION NUMBER	1W		3E		4E		5W		7E		13W	
ASH COMPOSITION WEIGHT PERCENT	FLY ASH	COAL ASH	FLY ASH	COAL ASH	FLY ASH	COAL ASH	FLY ASH (a)	COAL ASH	FLY ASH	COAL ASH	FLY ASH	COAL ASH
Li_2O	0.02	0.01	0.03	0.03	0.04	0.04	0.02	0.02	0.05	0.05	0.01	0.01
Na_2O	0.29	0.27	0.67	0.63	0.43	0.44	1.38	1.28	0.27	0.31	1.42	1.51
K_2O	1.8	1.0	2.1	2.1	3.5	3.2	0.54	0.53	2.1	2.2	1.0	0.9
MgO	3.6	2.8	1.0	1.0	1.3	1.2	1.1	1.8	0.9	0.9	1.8	1.9
CaO	8.6	7.5	5.0	4.6	1.1	1.0	5.8	5.3	3.7	3.2	6.7	7.3
Fe_2O_3	5.9	6.0	13.1	9.0	7.2	7.4	6.1	2.5	7.1	6.8	5.0	5.7
Al_2O_3	23.7	15.2	21.8	25.4	28.4	28.4	13.2	13.7	29.3	29.4	25.5	21.6
SiO_2	51.9	65.3	50.2	53.3	53.8	53.3	70.8	73.6	53.5	54.4	56.3	57.8
TiO_2	1.3	1.2	2.0	1.6	1.8	1.9	0.9	1.2	1.8	1.6	1.0	0.5
P_2O_5	0.39	0.35	0.78	0.21	0.23	0.24	0.05	0.13	0.20	0.33	0.31	0.3
SO_3	1.2	0.58	2.3	0.77	0.50	0.15	0.50	0.63	0.7	1.6	0.71	3.5
TOTAL	98.7	100.2	99.0	98.6	98.3	97.3	100.4	100.7	99.6	100.8	99.8	101.0
LOI	0.8	-	10.9	-	3.5	-	1.0	-	7.5	-	2.6	-
SOLUBLE SULFATE	0.7	-	1.6	-	0.3	-	0.5	-	0.7	-	0.5	-
FLUE GAS COMPOSITION	IN SITU	PREDICTED	IN SITU	PREDICTED	IN SITU	PREDICTED	IN SITU	PREDICTED	IN SITU	PREDICTED	IN SITU	PREDICTED
CO_2, vol %	13	13	13	13	15	13	13	13	ND	13	15	13
O_2, vol %	7	5	5	5	5	5	6	5	ND	5	5	5
H_2O, vol %	8.3	9.6	8.2	8.4	8.5	7.8	8.1	10.5	9.0	8.2	9.6	9.1
SO_2 ppm	262	440	2440	1730	755	800	480	570	600	740	430	429
SO_3 ppm	<1	1.8	6-9	6.9	2-3	3.2	<1	2.3	3-4	3.0	<1	1.7

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a About 8% of this ash was > 0.18 mm (+80 mesh) and mostly carbon. It was removed prior to testing.

The predicted values for sulfur trioxide were within the range of values reported in the field test data for the stations burning eastern coal. However, the predicted sulfur trioxide concentration for the stations burning low-sulfur western coals was about 2 ppm while the _in situ_ value was < 1 ppm. Several possible explanations can be given for this observation. The _in situ_ measurement of sulfur trioxide is not a simple test, is subject to error, and is less reliable the lower the concentration of agent present. Also, 2 ppm is near the level of detection. On the other hand, the ashes from western coals are inherently more basic than ashes from eastern coals. This greater affinity for acid vapor coupled with the low available concentrations of sulfur trioxide could lead to an almost undetectable concentration remaining in the flue gas at the inlet to the precipitator. In the proof test experiments, the sulfur trioxide value determined from the stoichiometric combustion calculation was used to predict resistivity, while the _in situ_ value was duplicated in the experimental environment for the determination of laboratory resistivity.

Table XI shows a comparison of _in situ_ resistivity just prior to dielectric failure, laboratory resistivity just prior to dielectric failure, and predicted resistivity at a field strength of 10 kV/cm. The temperature listed refers to the temperature at which the _in situ_ determination was made and later duplicated during the laboratory measurement. Precipitator mass train efficiency and current density for the outlet field are also given as circumstantial evidence to help evaluate the quality of the resistivity determinations and prediction.

Figures 28 through 33 show the _in situ_ and laboratory resistivity data superimposed on a curve of predicted resistivity as a function of temperature for each of the stations evaluated. To illustrate the pronounced effect of sulfuric acid vapor on resistivity, the data are plotted with and without the effect of the predicted concentration of sulfur trioxide taken into account. The predicted resistivity under consideration in all cases except station 5 is the value obtained by including the effect of sulfur trioxide. In the case of station 5, the temperature of interest is significantly lower than the lowest temperature used to develop the predictive parameters involving sulfur trioxide.

The data illustrated in Figures 28 through 33 visually demonstrate the generally good agreement obtained between predicted and measured results. Only in the case of stations 5 W and 4 E was the deviation significant. In these instances, the _in situ_ resistivity data were about one order of magnitude greater than either the predicted or the laboratory measured data.

Table XI. Predicted Resistivity Proof Check
Temperature, Resistivity and Performance Data for Six Power Stations

STATION NUMBER	1W	3E	4E	5W	7E	13W
TEMPERATURE, °C	145	158	332	105	163	350
RESISTIVITY, ohm·cm						
In Situ Spark	3.0×10^{11}	2.1×10^{10}	3.0×10^{10}	5.0×10^{11}	2.7×10^{11}	1.8×10^{9}
Laboratory, Spark	5.0×10^{11}	2.3×10^{10}	4.0×10^{9}	5.0×10^{10}	2.2×10^{11}	2.0×10^{9}
Predicted, 10 kV/cm	1.2×10^{11}	7.0×10^{10}	2.3×10^{9}	1.6×10^{10}(a)	5.0×10^{11}	1.4×10^{9}
ESP EFFICIENCY, %	99.92	99.87	99.65	99.85	NA	99.22
CURRENT DENSITY	15	45	37	23	NA	13
OUTLET FIELD, nA/cm^2						

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a Test temperature below that of acquired laboratory data involving sulfur trioxide.

SYM	STATION	NAME	C/P	PR.	H_2O	O_2	CO_2	SO_2	SO_3	P%	E, kV/cm	mmd, μm	d, g/cc	DATE
□	1W	PREDICTED	–	–	9.6	5	13	440	1.8	–	10	–	–	–
○	1W	PREDICTED	–	–	9.6	5	13	0	0	–	10	–	–	–
△	1W	IN SITU	–	–	8.3	7	13	262	<1	–	SPARK	–	–	–
⬡	1W	LABORATORY	–	–	9.0	AIR		0	1.3	–	SPARK	–	–	–

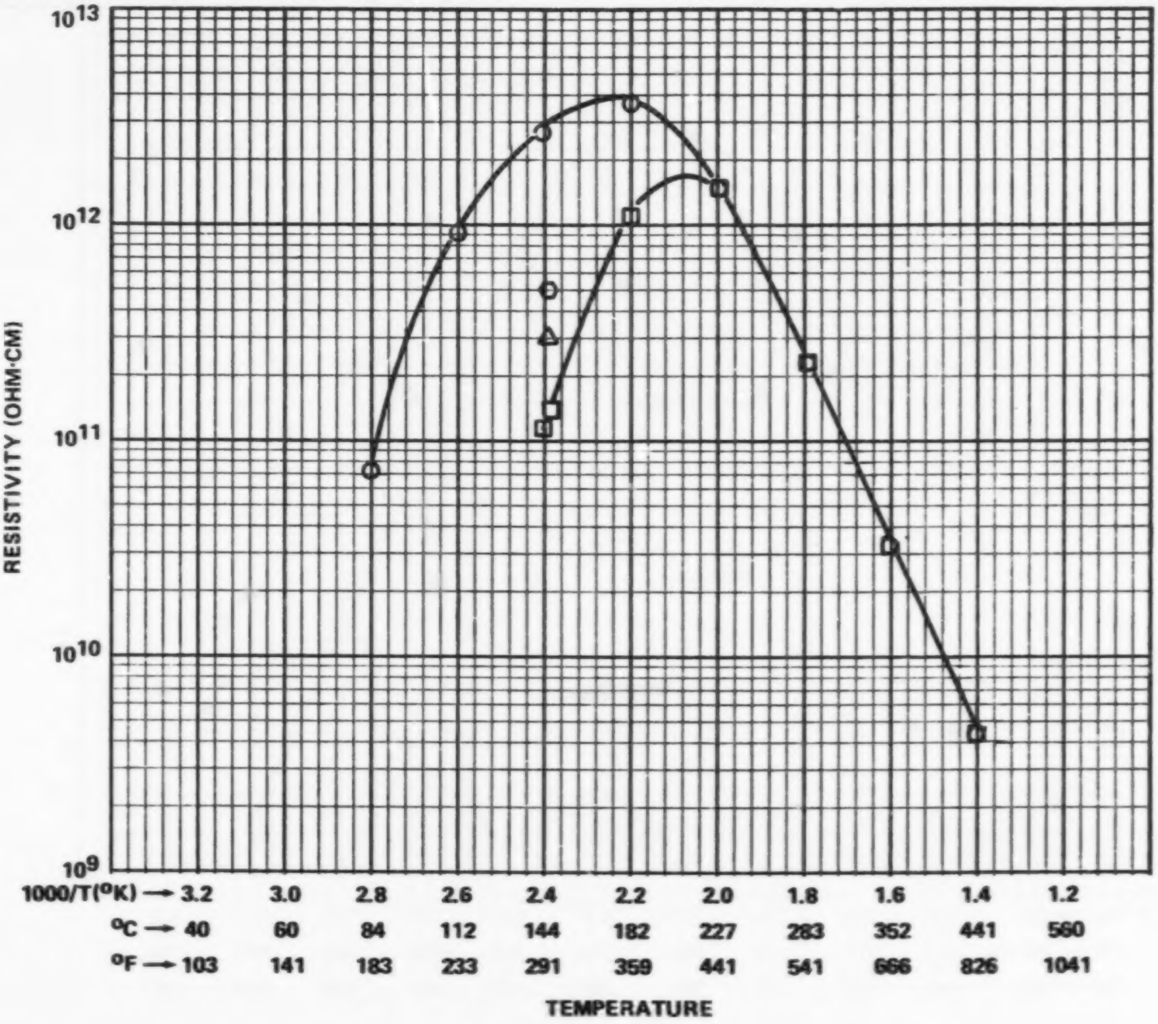

Figure 28. Predicted, in situ, and laboratory measured resistivity data, Station 1W.

SYM	STATION	NAME	C/P	PR.	H_2O	O_2	CO_2	SO_2	SO_3	P%	E, kV/cm	mmd, µm	d, g/cc	DATE
□	3E	PREDICTED	–	–	8.4	5	13	1730	6.9	–	10	–	–	–
○	3E	PREDICTED	–	–	8.4	5	13	0	0	–	10	–	–	–
△	3E	IN SITU	–	–	8.2	5	13	2440	(6-9)	–	SPARK	–	–	–
○	3E	LABORATORY	–	–	9.0	AIR		0	8.7	–	SPARK	–	–	–

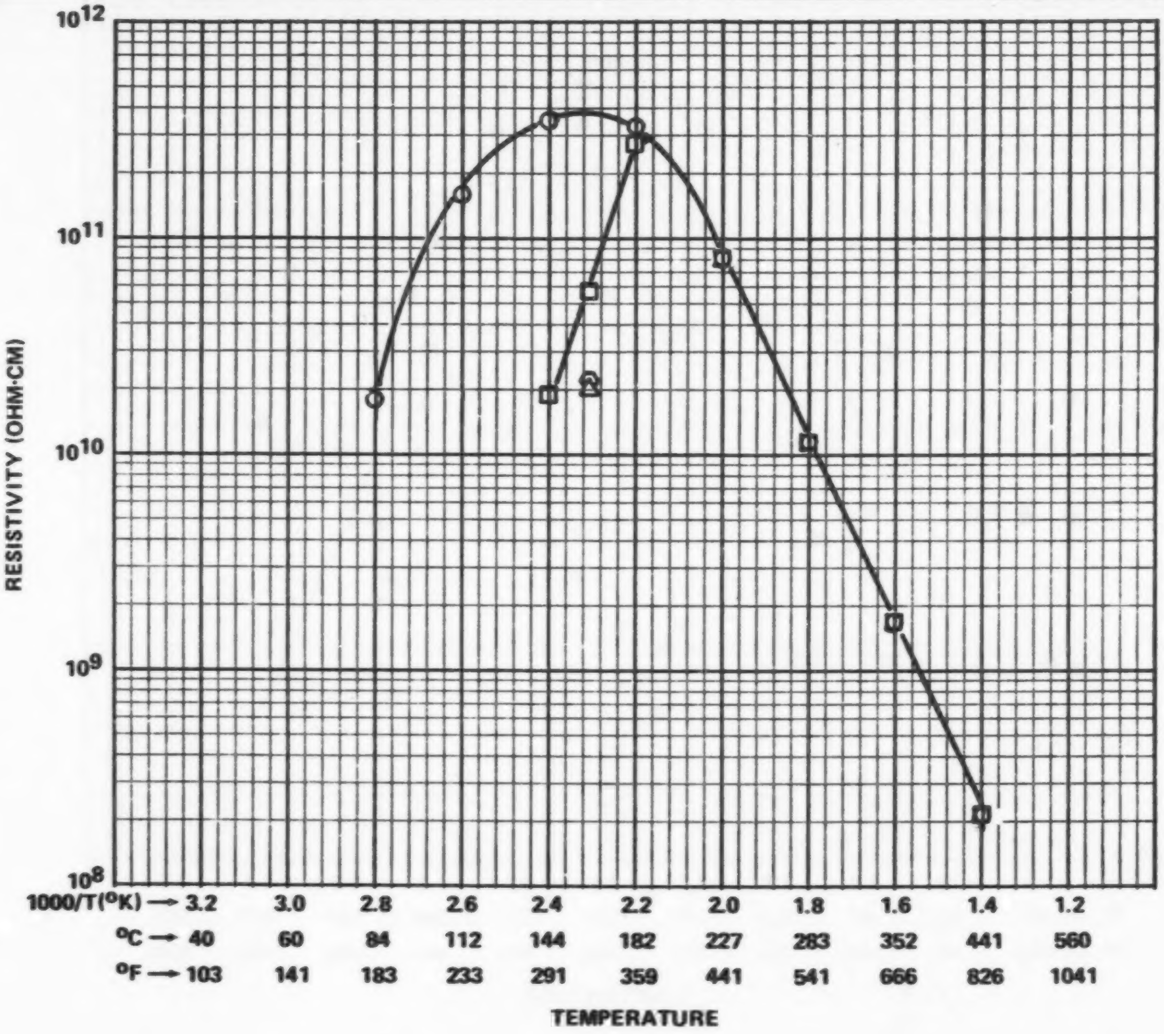

Figure 29. Predicted, in situ, and laboratory measured resistivity data, Station 3E.

SYM	STATION	NAME	C/P	PR.	H_2O	O_2	CO_2	SO_2	SO_3	P%	E, kV/cm	mmd, µm	d, g/cc	DATE
□	4E	PREDICTED	–	–	7.8	5	13	800	3.2	–	10	–	–	–
○	4E	PREDICTED	–	–	7.8	5	13	0	0	–	10	–	–	–
△	4E	IN SITU	–	–	8.5	5	15	755	2.5	–	SPARK	–	–	–
⬡	4E	LABORATORY	–	–	9.2	5	AIR		3.1	–	SPARK	–	–	–

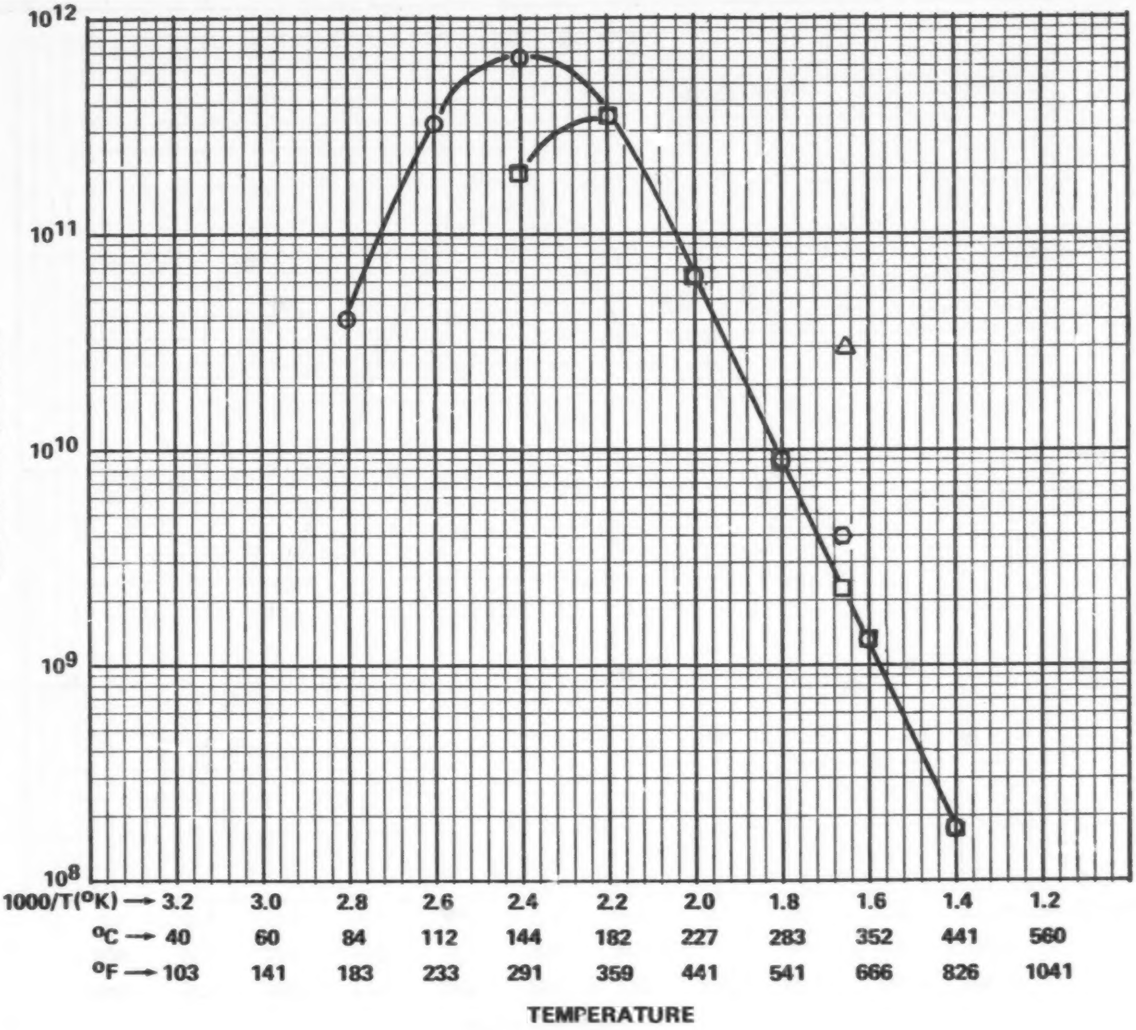

Figure 30. Predicted, in situ, and laboratory measured resistivity data, Station 4E.

SYM	STATION	NAME	C/P	PR.	H_2O	O_2	CO_2	SO_2	SO_3	P%	E, kV/cm	mmd, μm	d, g/cc	DATE
□	5W	PREDICTED	–	–	10.5	5	13	570	2.3	–	10	–	–	–
○	5W	PREDICTED	–	–	10.5	5	13	0	0	–	10	–	–	–
△	5W	IN SITU	–	–	8.1	6	13	480	1	–	SPARK	–	–	–
⬡	5W	LABORATORY	–	–	9.0	AIR		0	1.0	–	SPARK	–	–	–

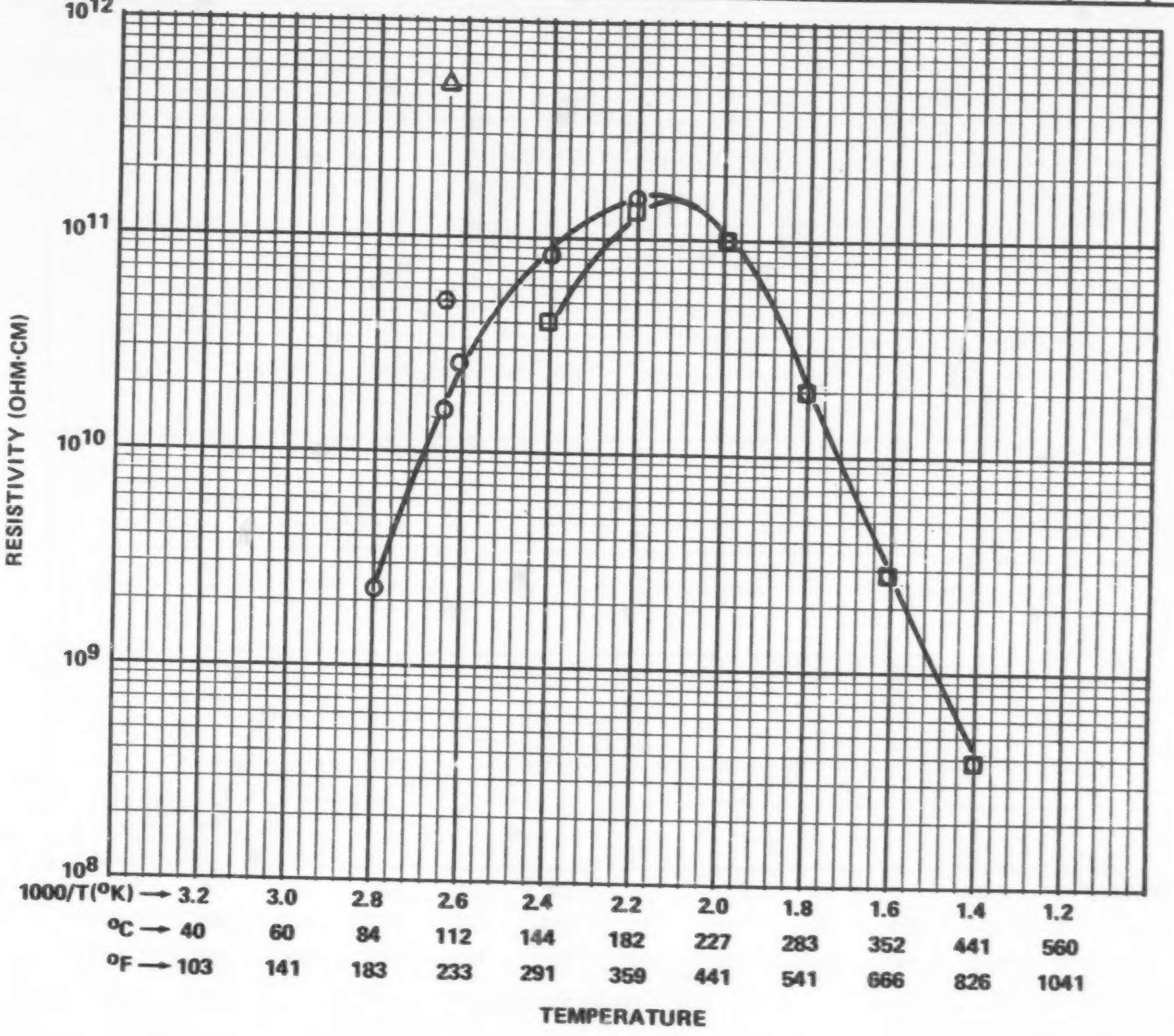

Figure 31. Predicted, in situ, and laboratory measured resistivity data, Station 5W.

SYM	STATION	NAME	C/P	PR.	H_2O	O_2	CO_2	SO_2	SO_3	P%	E, kV/cm	mmd, µm	d, g/cc	DATE
□	7E	PREDICTED	–	–	8.2	5	13	739	3.0	–	10	–	–	–
○	7E	PREDICTED	–	–	8.2	5	13	0	0	–	10	–	–	–
△	7E	IN SITU	–	–	9.0	ND	ND	600	3.0	–	SPARK	–	–	–
⬡	7E	LABORATORY	–	–	9.0	AIR		0	2.9	–	SPARK	–	–	–
◇	7E	PREDICTED	–	–	8.2	5	13	739	8.5	–	10	–	–	–
◆	7E	IN SITU	–	–	9.0	ND	ND	600	7-10	–	SPARK	–	–	–
▽	7E	PREDICTED	–	–	8.2	5	13	739	12.5	–	10	–	–	–
▼	7E	IN SITU	–	–	9.0	ND	ND	600	11-14	–	SPARK	–	–	–

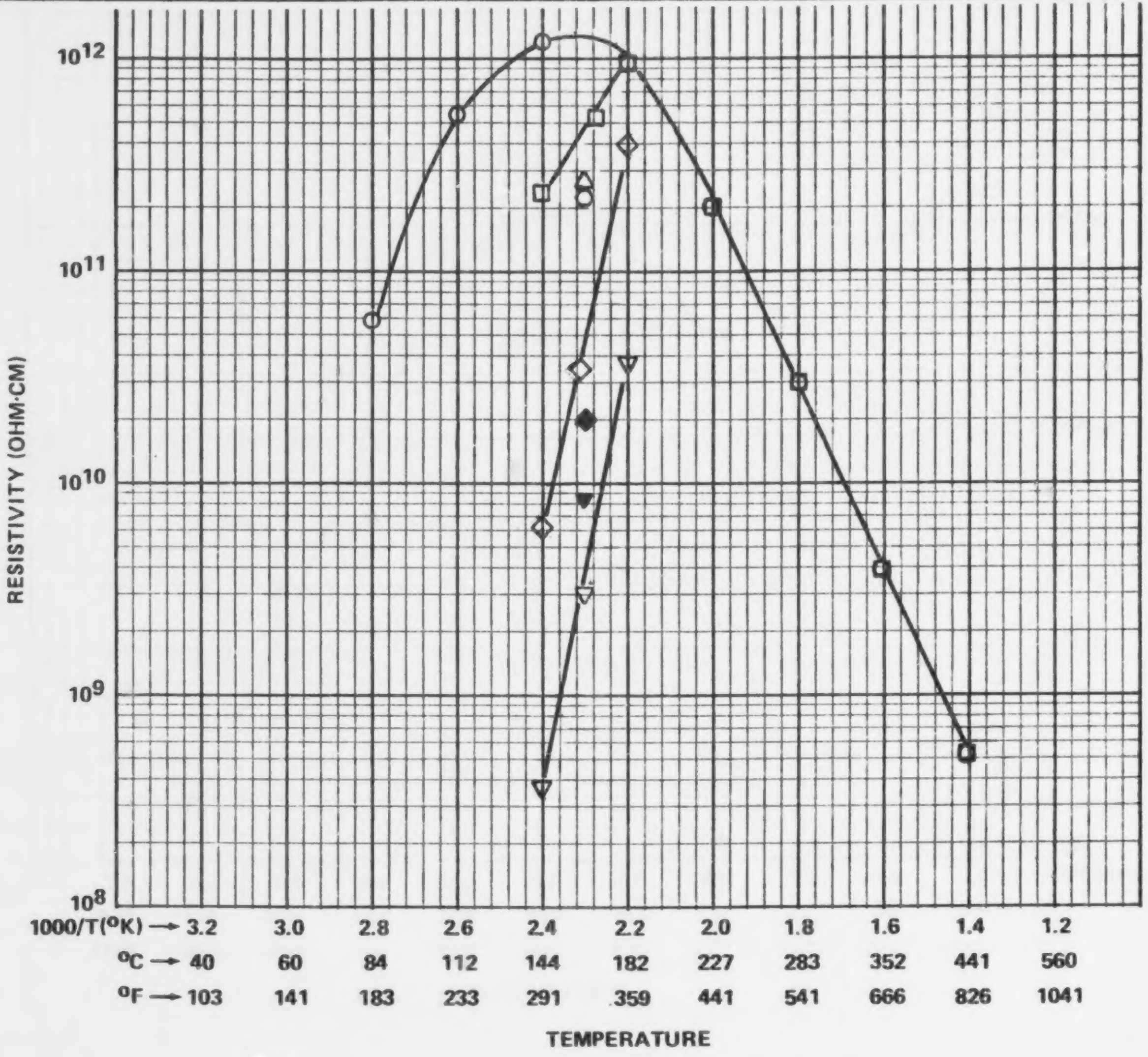

Figure 32. Predicted, in situ, and laboratory measured resistivity data, Station 7E.

SYM	STATION	NAME	C/P	PR.	H_2O	O_2	CO_2	SO_2	SO_3	P%	E, kV/cm	mmd, µm	d, g/cc	DATE
□	13W	PREDICTED	–	–	9.1	5	13	429	1.7	–	10	–	–	–
○	13W	PREDICTED	–	–	9.1	5	13	0	0	–	10	–	–	–
△	13W	IN SITU	–	–	9.6	5	15	430	1	–	SPARK	–	–	–
⬡	13W	LABORATORY	–	–	9.3	5	13	0	0	–	SPARK	–	–	–

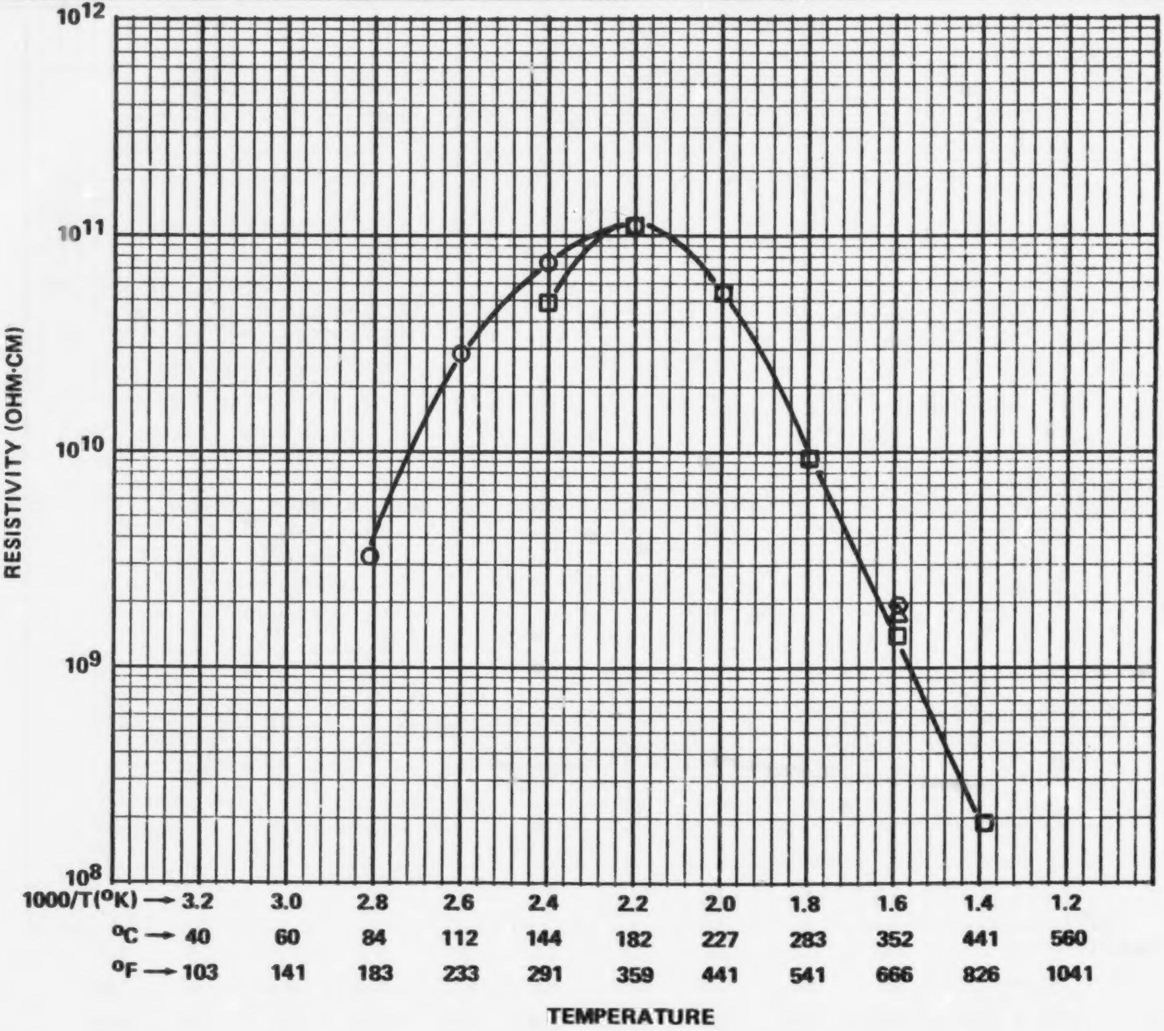

Figure 33. Predicted, in situ, and laboratory measured resistivity data, Station 13W.

Station 4 E is a hot-side unit burning eastern coal. Since both the *in situ* and laboratory measured resistivity values were in the desirable range, 3.0 x 10^{10} ohm cm and 4.0 x 10^{9} ohm cm respectively, it is difficult to assess the accuracy of either. The efficiency of the precipitator and the outlet field current density are commensurate with desirable levels of resistivity. It is noted that only one hot-side *in situ* resistivity measurement was made during the field test. This value was obtained with a new high temperature probe in service for the first time.

The other unit that showed a significant deviation was the cold-side unit burning a western coal, station 5 W. In this case the high efficiency of the precipitator and the reasonably high current density in the outlet field (23 nA/cm^2) suggest that for some reason the *in situ* resistivity is inaccurately high. It is pointed out that the power station in this case was having pulverizing-mill problems at the time of the field test, and a high percentage of coarse fly ash was produced. The point-plane *in situ* probe is inclined to preferentially collect a particle-size distribution that is coarser than normal. From the standpoint of specific surface and perhaps ash composition, this biased collection could lead to *in situ* resistivity values that are higher than anticipated. Another minor factor contributing to this deviation was the fact that the water concentration used in the resistivity prediction was over 2 volume percent greater than that measured *in situ*.

The predicted resistivity also can be evaluated by examining resistivity ratios in which a perfect correlation yields a ratio of unity. Three calculated ratios are shown in Table XII: *in situ* resistivity/predicted resistivity, laboratory measured resistivity/predicted resistivity, and laboratory measured resistivity/*in situ* resistivity. When it is considered that consecutive *in situ* resistivity measurements involving the point-plane probe have shown on occasion an order of magnitude variation and that a series of repeated laboratory determinations can develop a factor of 3.0 high/low ratio, the agreement among *in situ*, laboratory and predicted resistivity is excellent. With the exception of the two cases in which the *in situ* data are an order of magnitude greater than both the predicted and laboratory-measured data, one could not expect better agreement.

The results pertaining to station 7 E require additional explanation. This station was burning a coal that had been cleaned to reduce the ash and sulfur content from 20-25% and 1.5-2.0% to <12% and <1% respectively. First, it was desired to evaluate the resistivity prediction for a cleaned coal. These results were included above; that is, *in situ* and laboratory measured resistivity was 2-3 x 10^{11} ohm cm and predicted resistivity was 5 x 10^{11} ohm cm.

Table XII. Comparison of Predicted Resistivity Values with those Measured in the Laboratory and *In Situ*

		Resistivity Ratio		
Station	T, °C	$\frac{\text{In Situ}}{\text{Predicted}}$	$\frac{\text{Laboratory}}{\text{Predicted}}$	$\frac{\text{Laboratory}}{\text{In Situ}}$
1 W	145	2.5	4.2	1.7
3 E	158	0.3	0.3	1.1
4 E	332	13.0	1.7	0.1
5 W	105	31.3	3.1	0.1
7 E	163	0.5	0.4	0.8
13 W	350	1.3	1.4	1.1

In anticipation of elevated resistivity due to the lowering of the coal's sulfur content by cleaning, the utility had available a commercial sulfur trioxide injection system to condition the ash. This afforded an opportunity to compare in situ and predicted resistivity values for sulfur trioxide conditioning.

Two injection concentrations were used, nominally 25 and 15 ppm. These injection rates at the precipitator inlet produced measured sulfur trioxide concentrations of 11-14 ppm and 7-10 ppm, respectively. Resistivity was predicted for these injection rates using the coal and coal ash analyses shown in Tables IX and X, respectively, except that the calculated sulfur trioxide value of 3 ppm based on the coal's sulfur content was replaced by the average values measured at the precipitator inlet, namely, 12.5 and 8.5 ppm. These predicted resistivity values and the resistivity data measured in situ are shown in Figure 32. At the temperature of interest, the predicted resistivity using 12.5 ppm sulfur trioxide was 3×10^9 ohm cm while the in situ measurement was 9×10^9 ohm cm. The prediction for 8.5 ppm sulfur trioxide was 3×10^{10} ohm cm and the in situ measurement was 2×10^{10} ohm cm. These results are very encouraging with respect to the resistivity prediction technique. One cannot critically review the variance shown with respect to the method of prediction. It is obvious that the resistivity is very sensitive to temperature and sulfur trioxide concentrations. Because of this sensitivity, small deviations in temperature and the lack of information about the concentration of sulfur trioxide at the precise time and the exact region of the in situ resistivity probe measurement can cause the resistivity data to agree or disagree with the predicted value.

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